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MTL TR 87-23

COMPUTER CONTROLLED RESIN IMPREGNATION FOR COMPOSITE BRAIDING

April 1987

AUGUST H. KRUESI and GREGORY H. HASKO
U. S. Composites Corporation
Rensselaer Technology Park
105 Jordan Road
Troy, NY 12180

FINAL REPORT

Contract DAAG46-85-C-0059

Approved for public release; distribution unlimited.

Prepared for

U.S. ARMY MATERIALS TECHNOLOGY LABORATORY
Watertown, Massachusetts 02172-0001

UNCLASSIFIED
SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER MTL TR 87-23	2. GOVT ACCESSION NO. AD-A181 401	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) COMPUTER CONTROLLED RESIN IMPREGNATION FOR COMPOSITE BRAIDING		5. TYPE OF REPORT & PERIOD COVERED Final Report Sept. 1985 - Dec. 1986
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) August H. Kruesi and Gregory H. Hasko		8. CONTRACT OR GRANT NUMBER(s) DAAG46-85-C-0059
9. PERFORMING ORGANIZATION NAME AND ADDRESS U.S. Composites Corp. Rensselaer Technology Park, 105 Jordon Road Troy, NY 12180		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS D/A Project: 1L665502MM40 AMCMS Code: 665502.M40
11. CONTROLLING OFFICE NAME AND ADDRESS U.S. Army Materials Technology Laboratory ATTN: SLCMT-ISC Watertown, MA 02172-0001		12. REPORT DATE April 1987
		13. NUMBER OF PAGES 67
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Braids
Composite materials
Processing
Automation
Material forming

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

(SEE REVERSE SIDE)

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

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Block No. 20

ABSTRACT

Textile processes such as braiding may significantly reduce the cost of advanced composites. Braiding can be readily automated and offers high fiber deposition rates and geometric versatility. Previously, the use of braiding was limited because of the difficulty in wetting fibers moving in a complex path. A novel resin impregnation system has been developed to adapt braiding to automated production of advance composites. A tubular braider has been equipped with a computer numerical control system. Two axes are used to drive pumps which feed resin and catalyst to the resin impregnation ring. The mix ratio and resin volume fraction can be coordinated in software with braider and mandrel speeds to fabricate parts which have complex features. Test specimens have been fabricated with glass, Kevlar, and carbon fibers. Fiber wetting and void content were evaluated from microphotographs of parts cured on a mandrel without compaction. Burn-off tests indicated that fiber volume fractions are in excess of 60 percent. Applications for the process include space station tubes, rocket motor cases, launch tubes, gun barrel reinforcement, rotor blades, stiffeners, drill risers, and similar structural components. This work was supported by the U.S. Army Materials Technology Lab under the Small Business Innovation Research (SBIR) program.

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1. Introduction

The fabrication of composite structures using preimpregnated (prepreg) fiber materials is now highly developed. However, the cost of composites manufactured with pre-pregs is prohibitively high for many applications. Automated, low-cost fabrication technologies are needed to allow the use of composites in cost-sensitive products such as ground vehicles, bridging, and shelters. Budgetary constraints are also driving the use of automated manufacturing for flight vehicle components. Textile processing techniques such as braiding offer potential advantages in composite fabrication. For example, tubular braiding equipment can weave a seamless fiber ply around a mandrel at a precise angle. Braiders are readily automated and achieve high production rates. Complex, non-circular shapes can be braided, and threaded plugs may be overbraided in a single operation to form a high reliability end fitting. Braided composites also have unique properties which can be advantageous in damage-tolerant and energy-absorbing structures. Examples of braided composites are shown in Figure 1.

McDonnell Douglas Astronautics Co. initiated the use of braided composites in high volume applications including fiberglass/epoxy launch tubes, ducting, and fuel lines (1,2). Recently other companies have used braiding to fabricate helicopter rotor spars, bridge truss tubes, and space station elements (3,4,5). U.S. Composites' engineers first employed braided composites in the development of a 7.5 m diameter wind turbine system (1980-1982); three braided rotor blades were built and successfully tested during 1,000 hours of operation over a two-year period. This experience with braiding led to the conclusion that braiding required a) automation and b) a reliable, on-line resin impregnation system in order to be used in production applications.

An innovative concept was developed by U.S. Composites to solve the resin impregnation problem: a ring shaped resin application device would be attached to the braider to wet the individual fiber tows prior to the braid convergence point. The ring surface is porous to allow uniform impregnation over 360° of the ring. Small beads of resin form over each of the pores. Because of the small pore diameter, the resin surface tension prevents uncontrolled dripping. As a fiber bundle passes over each pore, the surface tension is broken and resin wicks into the bundle. Wetting is assisted by contact pressure and by mechanical working due to the combined radial and tangential fiber motion. The porous surface is supplied with resin through a segmental plenum, so gravity effects on the ring are negated. U.S. Patent 4,494,436 has been awarded on the resin applicator system, and additional U.S. and foreign patents are pending. After completing some simple tests of the concept, U.S. Composites proposed a two-phase development program to the Army Materials Technology Laboratory, Watertown, Massachusetts under the Small Business Innovation Research (SBIR) program. This report outlines the work performed under the resulting Phase I and II contracts.

2. Program Objectives

The objectives of the SBIR contracts were two-fold: a) to conduct a production-scale demonstration of the resin applicator ring and b) to generate needed data on the properties of wet-braided composites using high performance fibers and resins. It was first necessary to establish performance goals for the system. The primary criteria was the ability to consistently produce composites with a high fiber volume fraction and low void content when

operating at normal braiding speeds. Technical literature was studied for comparative figures. Wet filament wound components can have void contents ranging from 3 to 8 percent (6). The lowest void contents in braided composites were 2.46 to 2.75 percent measured in a vacuum resin impregnated rotor spar (3). The goals subsequently established for the production braiding system are listed in Figure 2. These goals were for the lowest cost approach--wet braiding and oven curing on the mandrel without compaction.

FIGURE 2
PERFORMANCE GOALS FOR THE PRODUCTION COMPOSITE BRAIDING SYSTEM

- Apply liquid resin in a controlled manner during all modes of braiding: biaxial, triaxial, and bi-directional.
- Achieve the predicted fiber volume fraction within $\pm 4\%$. Maintain consistency of fiber volume fraction within $\pm 2\%$.
- Achieve a void content of less than 3% without shrink tape, vacuum bags, or other means of compaction.
- Automate the system with computer numerical control.
- Allow for the optional use of resin heating or cooling and resin de-aeration.

3. System Description

Standard tubular braiding machines manufactured by Mossberg Industries, Cumberland, R.I. have been adapted for use as composite braiders. A prototype production system was first tested at U.S. Composites on a 64 carrier machine (Figure 3). Later, a large scale (450 mm bore) resin applicator ring was installed on a 144 carrier braider installed in the Benet Weapons Laboratory at Watervliet Arsenal. A similar 144 braider at U.S. Composites is shown in Figure 4.

The resin applicator ring system consists of a laser-drilled porous ring with resin distribution plenum, adjustable mounting arms, and reversing ring assembly. The ring is supplied with resin by a pair of precision gear pumps driven by AC brushless servo motors (Figure 5). The resin and catalyst are mixed in a static mixing head on the back of the resin plenum, so the quantity of catalyzed resin is very small. The drive motors are AC induction motors controlled in a servo loop. This represents the latest technology in servo systems. Each motor has an optical shaft encoder for feedback control. The servos are commanded by an IBM PC equipped with a two-axis, motion-control board (two boards are used in the four-axis control system).

A program entitled "BRAID" was written to predict braiding parameters and thus minimize trial and error testing of new applications. Inputs include part diameter, fiber angle, braid speed, fiber type and denier, and bundle aspect ratio. The output includes predictions for ply thickness, fiber volume

fraction, coverage, mandrel speed, resin flow rate, and weight of material deposited per ply. This information is easily entered into the braider control computer. The machine operator can start the automatic cycle, interrupt, and resume operation at will using a single pushbutton. Any number of control programs for specific parts can be stored on floppy disk for later use.

4. Summary of the Test Plan and Results

A test plan was prepared to answer key questions about the resin applicator ring and the computer controlled pumps:

- o How accurate is the pumping system over the range of component viscosities, mix ratios, and flow pressures?
- o Is the segmented plenum effective in distributing resin evenly around the ring?
- o How well are the performance goals (Figure 2) met by the system?
- o What are the mechanical properties of wet-braided composites?

The pumping system was tested by measuring the volume flow rates using typical epoxy components: Epon 826 resin (6.5-9.5 Pa-sec) and MTHPA catalyst (.05-.08 Pa-sec). The results agreed with predictions within 1% for pressure differentials up to 275 kPa (40 psi). The resin mix ratio was verified by high pressure liquid chromatography (HPLC) tests of resin samples collected from the face of the ring. Four tests were conducted using two volume flow rates and two pumping pressures. Using a sample weighed with an analytical balance as a reference, the average error was 0.35% and the maximum error was 1%.

The flow distribution around the ring was tested by measuring the flow at the 12:00, 3:00 and 6:00 positions using epoxies with a mixed viscosity of 0.8, 1.9, and 2.9 Pa-sec. These tests showed that the plenum design enabled control of distribution to within 5% if desired.

The Army Materials Technology Laboratory had extensive data on the properties of $\pm 45^{\circ}$ filament wound tubes made of S2 glass, Kevlar, and carbon fiber, and an anhydride cure epoxy, Epon 828/MTHPA/BDMA. To obtain comparative results, it was decided to fabricate sets of wet-braided test specimens using the same materials, size, and fiber angle. Some additional specimens were fabricated using a $0/\pm 45^{\circ}$ triaxial construction and using other epoxy systems. Static tension, compression, and torsion tests are being conducted by the Army Materials Technology Laboratory and will be reported separately.

Operational tests have demonstrated that glass, Kevlar, and carbon yarns can be readily wet braided with any resin suitable for filament winding. Dow Tactix (TM) 138/H41 epoxy offered the best combination of physical properties and processing behavior of the various resins tested. Biaxial and triaxial

braiding tests were conducted in both forward and reverse directions at normal braiding speeds. The only material that had proven difficult was untwisted carbon tow; excessive damage occurred as the fibers threaded through the carrier mechanism. Since then, modified carriers have been installed to allow braiding with carbon tows. The set-up and cleaning procedures for the resin applicator ring are not difficult. The use of computer controls has led to excellent consistency of results when tests are repeated.

A key question was the adequacy of wetting of individual filaments by the resin applicator ring. To answer this concern, a number of test specimens were sectioned and examined by microphotographs. A cross section of wet braided Kevlar/epoxy shows excellent wetting (Figure 6). Elliptical-shaped fiber bundles surrounded by resin rich zones are characteristic of braided composites (Figure 7). Voids that are found in the cross section are usually confined to the resin rich zones and are circular in shape. They appear to be caused by air bubbles present in the resin or by volatiles generated during cure. Resin de-aeration and vacuum bagging prior to cure are expected to reduce the void content to levels found in autoclave cured parts. Multiple ply laminates up to 12 mm thick have been wet braided without any sign of fiber wrinkling or other defect.

5. Resin Applicator Ring (RAR) Design

The basic technical question of the Phase II work was how to duplicate the fiber wetting behavior of a unit cell developed in Phase I over a 360° ring mounted in a vertical plane. A related concern was to retain resin over the entire flow area during standby conditions; i.e., to prevent draining during pauses in braider operation. About 1/2 psi pressure head exists per foot of ring height. Provisions must be made in the design to cover wide ranges of flow rates and resin viscosities in order to accommodate a variety of part geometries and resin systems without major redesign.

Another factor to be evaluated was the degree of flow uniformity over the full circumference of the ring that is required to avoid maldistribution on the final part. One method of achieving uniform flow that was considered is the use of pressure compensated flow controls in multiple lines to feed sectors of the ring. Commercial products used in hydraulic power circuits were investigated and found to be costly, cumbersome, and not stocked in the low flow rates and pressures involved. A design was therefore conceived having one feed line and internal porting and baffling to distribute flow.

The overall approach taken to meet the design goals is to provide four stages of flow breakup from a single inlet port into a plenum. The first stage is an enclosed distribution channel that runs around the circumference of the ring. Fluid access from this channel to the zone just behind the cover plate is provided by uniformly spaced ports. Pins are provided to close down the flow area through these ports. The pressure drop for a given flow rate and viscosity is inversely related to the flow area, so pins are sized to cause sufficient pressure drop to overshadow gravity head effects.

The second stage of flow breakup occurs when the fluid exits the ports and spreads into a thin, approximately square zone just behind the face of the

cover plates. Boundaries of the zone are formed by the inside and outside diameters of the cover plate and by foam divider strips inserted radially around the ring.

The third stage of smoothing the flow is provided by a layer of filter paper just behind the porous cover plate. This layer adds some flow resistance, allowing the fluid to spread into the gap with square boundaries. Flow resistance can be varied by changing the grade of filter paper, or omitting it. The fourth stage is an extension of the third, whereby the porous cover plate adds a degree of flow resistance.

Design details are shown in the assembly and detail drawings for the RAR64 and RAR450 (see References 14-18). Prior to fabricating these parts, two prototype RAR's were made using epoxy castings. The castings were made using metal cooking utensils as molds. Plenum chambers were formed with paraffin, which was melted out after the epoxy cured. Holes were drilled with a small diameter steel drill bit. Dimensions are compared in the following table:

	Small Epoxy	Large Epoxy	RAR64	RAR450
Cover OD	4.25"	12.00"	13.00"	22.28"
Cover ID	2.375"	7.00"	7.875"	17.72"
Hole Dia	.020"	.020"	.0155"	.015"
Number of Holes	500	1,080	7,920	10,080
Number of Pins	---	---	16	36
Pin Type	---	---	Round	Notched
Channel Type	---	---	Sandwich Plate	Peripheral
Plenum Type	4 Ports, Solid Dividers	1 Port, No Dividers	Foam Dividers	Foam Dividers
Seals	---	(1) Sheet	(2) Face	(2) Face and O-Ring

The largest expense is laser drilling of the cover plate holes, so they are sized to accommodate high flow rates of high viscosity resins. For lower flow conditions, pins and filter paper are selected accordingly. The type of flow is basically laminar, analogous to controlled leakage. Flow pressure is directly related to flow rate, fluid viscosity, and flow resistance:

$$P = f(Q,\mu,R)$$

Flow restrictor pins are designed using the following equations (Ref. Rothbart):

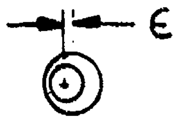
Circular Tube:

$$\Delta P = \frac{128\mu QL}{\pi D^4}$$

Concentric Annulus

$$\Delta P = \frac{12\mu QL}{\pi D h^3}$$

$$h = \left[\frac{D - d}{2}\right]$$



Eccentric Annulus

$$\Delta P = \frac{12\mu QL}{\pi D h^3 \left[1 + 1.5(c/h)^3\right]}$$

Non-Circular Tube

$$\Delta P = \frac{128\mu QL}{\pi \left[\frac{4 \times \text{Area}}{\text{Perimeter}}\right]^4}$$

The resin flow rate is a function of the flow rate of fibers encountered in the braiding process.

Braiding is similar to a filament winding process in that the fiber spools rotate around a circular frame and the fibers are pulled out along the centerline of the frame. The basic fiber parameters are shown in Figure 8, and a fully loaded braider with resin applicator ring is shown in Figure 3. Braiding parameters are related by the following equations:

1. Mandrel Velocity — $V = \omega \pi D/\text{tangent}\,\alpha$
2. Fiber Angle for Full Coverage with No Bunching — $\alpha = \text{Arccos}\left[\frac{WN}{2\pi D}\right]$
3. Fiber Wrap Pitch Length — $h = \pi D/\text{tangent}\,\alpha$
4. Fiber Projected Length Per Revolution — $L = \pi D/\text{cosine}\,\alpha$
5. Ply Weight Per Unit Length — $W = (NL\rho_L)/(h)$

$$\rho_L$$

Fiber weight per unit length on spool

6. Fiber Volumetric Flow Rate

$$Q_F = \rho_F WV$$

ρ_F = Fiber weight per unit volume

The fiber flow rate is a function of braider size, fiber bundle size, braider speed, and mandrel speed. For a given part being fabricated, the fiber weight per ply is known. Braider speed and mandrel speed are set to achieve the proper fiber angle; the total volumetric fiber flow rate can, therefore, be calculated. The resin flow rate is then set to achieve the fiber-to-resin ratio desired in the final cured part.

Total Mixed Resin Flow Rate

$$Q_R = Q_F\left[\frac{1}{\upsilon_F} - 1\right]$$

υ_F = Fiber volume fraction

Component Flow Rate Percentage

$$\%\ \text{Epoxy} = \frac{1}{\frac{\rho_E}{\rho_H M} + 1}$$

Where ρ_E = Density of Epoxy
ρ_H = Density of Hardener

$$M = \text{Mix Ratio} = \frac{\text{Parts by weight of Epoxy}}{\text{Parts by weight of Hardener}}$$

Some adjustments to the theoretically correct resin flow rate can be made after observing resin squeezing and dripping behavior after compaction onto the mandrel. Typical resin flow rates are on the order of 10 to 100 milliliters per minute.

These equations were used in writing a computer program call "BRAID" for the IBM personal computer. A sample copy ofthe output is shown in Figure 9. The program is written on a diskette (Reference 7).

Provision is made for heating the ring in order to reduce the viscosity of resins that are too viscous for room temperature use. Components are

designed to give adequate sealing under normal conditions and allow for quick disassembly for cleaning.

6. Resin Delivery System

Due to the wide range of viscosities of resins and catalysts (5 to 20,000 cps at room temperature) and the need to adapt to computer control, gear pumps were selected to deliver resin to the RAR. In theory, gear pumps discharge an exact volume of fluid per revolution. However, this is only true for certain ranges of speed, fluid viscosity, and pressure differential across the pump. Gear pumps are not designed with chamber seals, but depend on precise machining to reduce clearance between gear faces and the housing plates. This clearance is a potential leak path for fluids to short circuit around the gear teeth, which would alter the actual flow through the pump. If a pressure difference exists between the pump inlet and outlet, fluid can seep through even with the rotor locked. The rate of this flow increases with the cube of the clearance, linearly with pressure, and inversely with viscosity.

The volumetric efficiency of a pump is:

Ref. Rothbart

$$\eta_v = 1 - C_s \left[\frac{P}{\mu N} \right] = \frac{Q \text{ Actual}}{Q \text{ Theoretical}}$$

Where: Cs = Slip Coefficient
P = Pressure Drop Across the Pump
μ = Fluid Viscosity
N = Pump Speed

The slip coefficient is proportional to the cube of the typical clearance of a pump. The volumetric efficiency can be held to 100 percent if $\Delta P = 0$. If the $\Delta P \neq 0$, the pump efficiency can be very high for viscous fluids. Low viscosity fluids, however, may cause the volumetric efficiency of a given pump to decrease unacceptably. Also, cavitation can result if the pump is run at too high a speed, which would also degrade volumetric efficiency.

There are ways to compensate for volumetric inefficiency of a gear pump. If tests show that leakage is a problem with a fluid of too low a viscosity, a pressurized reservoir can be set to maintain zero pressure difference across the pump. Downstream pressure is a function of the mixed viscosity, flow rate, and resistance of the mixer and RAR. If rotational speed is too high for a given size pump and cavitation results, a larger pump can be used.

Once volumetric efficiency for a given pump and fluid combination is assured, flow rate is directly proportional to rotational speed. As long as the torque limit of the motor is not exceeded, flow accuracy is a function of control system accuracy. Refer to Appendix A for details of the pump drive system.

For the particular resin system and flow rate of interest, the pump manufacturer recommended two different pump sizes: ".160" cc/rev. for catalyst, and ".297" cc/rev. for resin. After measuring actual volume delivered versus number of pump revolutions (Figure 10), it was discovered that the .160 size actually delivers .172 cc/rev. This result was later confirmed by the manufacturer. Evidently their sales information has not kept pace with engineering changes.

The small pump was then set up for a bench test to measure flow rate versus speed while changing pressure differential across the pump. Upstream pressure was set by pressurizing the resin tank. Downstream pressure was varied with a throttle valve. The fluid used was the catalyst MTHPA. Differential pressure was 10 psi inlet side to 30 psi outlet side. Flow rates were 5.3, 10.8, and 16.2 ml/min. As shown in Figure 11, pump delivery was constant under these conditions.

Next, both pumps were set up to feed into the static mixer having the throttle valve at the outlet. Epon 826 was pumped with the large pump and MTHPA was pumped with the small pump. Pressure differential was set from 6 psi inlet side, up to 40 psi outlet side. Pump motor controls were set to the proper mix ratio and total flow rate. At two delivery settings, the total system response was constant as shown in Figure 12.

Prior to using the above pumps, gear pumps of a different style were evaluated. These pumps had a magnetic coupling between motor shaft and pump gears instead of a pump shaft and seal. Also, the metering chamber consisted of a machined graphite insert inside a sheet metal enclosure. It was thought that this design would eliminate potential leakage around a pump shaft and would be easier to clean than a conventional design; however, difficulties occurred during operation. In the course of making test specimens over several hours, pump performance degraded for unknown reasons. Flow of one pump of the two component system fell off, causing an improper mix ratio and a reduction in total flow. For this reason, the magnetically coupled pumps were not used again, and the pump/motor stand was modified to accept the shaft-driven gear pumps. Possible causes of performance degradation of the magnetically coupled pumps are slippage of the magnetic coupling field or fluid slippage around the graphite metering chamber.

Two-component resin systems are mixed just prior to entry into the RR by a static mixer tube. The tube has internal helical baffles that blend the two streams as they flow along the length. Mixing efficiency depends on the viscosities of the two resins and the mix ratio. The closer the viscosities and flow rates of the two streams, the quicker they blend together. Poor mixing through a given mixer can be improved by increasing mixer length, or adding length incrementally. Mixer performance is very difficult to predict, so the blending efficiency and pressure drop should be tested for a given resin system at the flow rates required. The final viscosity of the fluid exiting the mixer also depends on the component viscosities and mix ratio and is also difficult to predict. Viscosity of the blend should be measured using the proper apparatus, such as a Brookfield viscometer.

The total flow rate exiting the mixer can be measured, and if it equals the sum of the two flow rates set at the pumps, the correct mix ratio is

assumed. However, to verify correct mixing with random sampling during operation, analytical chemical techniques are needed. One such technique is High Pressure Liquid Chromatography (HPLC). The constituent molecules of a substance will yield a characteristic chromatogram, which consists of a plot having a series of peaks. If the area under a peak is known for a pure sample of a resin, the mix ratio can be determined by measuring the area of that peak of a mixture of resin and hardener. Epon 826 has a very large peak caused by a monomer in its composition, which is a convenient benchmark. A typical output is shown in Figure 13. The monomer peak of interest is labeled "4.23". The corresponding area under the peak is listed in the table in the figure.

A set of four flow tests were conducted and the results were analyzed by HPLC. The objectives of these flow tests were to a) verify the accuracy of the two component resin pumping system and b) determine the effect of pressure differentials across the pumps on the accuracy of the system. These tests were important because measurements of the volume flow rate of each component do not guarantee the accuracy of flow rates when the two components are combined in a manifold and pumped through a flow restriction such as the static mixing head and resin applicator ring.

A schematic of the HPLC flow test apparatus is shown in Figure 13. This arrangement is identical to that of the resin applicator ring system except for the throttle valve. Use of the throttle valve simulated the pressure drop in the resin applicator ring while simplifying the collection of resin samples and allowing for adjustment of the pressure differential.

The braiding tests used the following epoxy system: Epon 826 (S.G. = 1.16), 100 parts by wt.; MTHPA (S.G. = 1.21), 80 parts by wt.; and BDMA accelerator (S.G. = 0.90), 1 part by wt. The BDMA, normally premixed with the MTHPA, was eliminated from the HPLC tests. The computer control was commanded to pump at two different flow rates (10 and 20 ml/min) which covered the range of flow rates typically used in the braiding tests. Because of the difference in densities of the Epon 826 resin and the MTHPA catalyst, the desired weight percents (55.25 wt.% resin and 44.75 wt. % MTHPA) were converted into equivalent volume flow rate proportions: 56.3 volume % resin and 43.7 volume % MTHPA. Given the total volume flow rate, percent flow contributed by pump number one and the pump chamber sizes in ml/revolution, the computer control is programmed to operate the two servomotors at the speed required to meet the desired volume flow rate and mix ratio.

By adjusting the air pressure supplied to the resin and catalyst tanks and adjusting the throttle valve position, the pressure differential across the pumps could be altered from -6 psi to +30 psi. The pump pressure differential during braiding will normally range from +10 to +30 psi. Four flow tests, designated P4-1, 2, 3, and 4, were conducted. A sample was collected from each test and placed in a freezer to minimize the reaction between resin and catalyst. Once the tests were complete, the samples were hand delivered to a nearby testing laboratory for HPLC analysis.

The testing laboratory first prepared a reference sample by weighing the resin and MTHPA components using an analytical balance. The two components were blended by rapidly hand stirring using a glass mixing rod. The reference sample was analyzed, then each of the four test samples was measured. The

results are presented in Table 1. The difference between the reference sample and the predicted result is attributed to the calibration of the HPLC machine. The four test samples are in close agreement with the reference sample results.

7. RAR Flow Tests (200 mm ID)

Flow distribution tests were conducted with the RAR assembled using the same flow resistance (pins and filter paper) to evaluate resin distribution over ranges of flow rate, pressure, and viscosity. The RAR was assembled with #14 pins (.182"o.d.) and ED 950-25 filter paper (low porosity). No static mixer element was used since pre-mixed resin of known viscosity was the test fluid. A pressure gage was placed at the RAR inlet port. One pump delivered the resin to the RAR.

A distribution sampling tool was made (see Figure 14), designed to quantify the volumetric flow rate from circular zones of the cover plate 1/2" in diameter. The tool consists of a plate having a gasket with a circular hole which forms an enclosed chamber when pressed against the face of the RAR. A hole is drilled through the plate to allow a piece of clear tubing to enter the chamber. The tube has a small bore, about 1/16", and has a gage length of 1" marked off. With resin flowing, the tool is placed against the face of the RAR. The time needed for flow between the gage length marks is recorded. The flow time at a given position on the RAR is then a reflection of the local flow rate.

The test fluid was a mixture of Epon 826 and MTHPA. The mix ratio was adjsuted to vary the mixed viscosity for each of three test runs. The values of mixed viscosity were 820, 1920, and 2930 cps. Results of RAR inlet pressure versus flow rate are shown in Figure 15 for each fluid run. Flow pressure increases linearly with flow rate for each fluid.

Flow pressure versus viscosity at 10 ml/min is shown in Figure 16. Although there is more scatter than in the data for flow pressure versus flow rate, the results show a linear increase in flow pressure versus viscosity of the fluid at the RAR inlet.

It should be noted that a different pressure response would result if a static mixer were placed between the gage and RAR inlet, if pressure were measured in the zone just behind the RAR cover plate, if different pins or filter paper were used, or if the RAR was heated. Also, flow pressure will be reduced if the system deviates from that of an enclosed rigid boundary filled with homogeneous liquid; i.e., if leaks open up or air is entrained in the resin. Also, if the viscosity of the fluid entering the RAR increases (due to loss of flow of the low viscosity component of a two-part resin system, for example), flow pressure will increase.

Flow distribution was measured with the sampling tool for each of the three test runs. The sampling technique is shown in Figure 17. Data for relative flow rates at 12:00, 3:00, and 6:00 positions on the ring are shown in Table 2. There is a general trend showing improved distribution as viscosity and flow rates are increased. Referring to Figure 15, these cases correspond to increasing flow pressure.

A more accurate method of measuring local flow rate would yield data with less scatter. One technique would be to soak up resin with a porous pad. The weight gain over a given time period can be measured with an analytical balance.

The flow pattern out of the face of the cover plate on the RAR starts at one plenum sector. A wavefront of fluid spreads out in both directions. The fronts meet as the last bit of air is pushed out of the RAR. Surface tension prevents resin from flowing until the RAR is full. The resin beads then break and fluid starts draining down, as shown in Figure 18.

8. Wet Braiding

Prior to wet braiding parts, a dry run is usually done with the RAR and braider configured for wet braiding. Any difficulties that may occur in this step are corrected prior to turning on the resin delivery system.

Motions that occur in braiding are similar to filament winding in that fibers are wound around a mandrel. The fiber angle on the mandrel is determined by the ratio of wrapping speed to the traverse speed along the mandrel axis. In braiding, fiber packages rotate around the braider frame while a non-rotating mandrel is fed through the center of the frame. The fiber packages are mounted on mechanisms that control tension, called "carriers".

The simplest braider configuration is for dry sleeving. Fibers are simply pulled from the carriers out to the braid point. Fibers thus form a cone, termed the "shed". At the apex of the cone is where the braided product is formed. The sleeve is pulled using a capstan, and the product is simply fed into a box for storage. To initiate a braid, fibers are pulled from each carrier and tied together to form a "pigtail".

Braiders are also capable of accepting axial, or warp fibers fed from racks behind the frame. These warp fibers pass through the axes of the gears that rotate the carriers. The resulting fabric, termed "triaxial", consists of fibers interwoven in three principal directions--axial and $\pm\,\theta$.

The RAR may be used to apply resin to fibers being formed into sleeving, with the RAR positioned to apply resin from the inside of the shed, as shown in Figure 19. A secondary braid ring is needed to hold fibers down against the face of the RAR as the finished sleeve is pulled away from the braider.

Structural parts are made on a braider by passing a mandrel through the frame, as shown in Figure 20, using a traverse mechanism. Fibers are compacted onto the mandrel at the braid point. Mandrels may become a permanent part of the final product, or may be removable after cure. The braided fibers conform to the shape of the mandrel, forming a continuous seamless skin. Multiple layers may be built up over a mandrel by reciprocating back and forth. At the end of each pass, the portion of the shed cone exiting the RAR must be inverted, as shown in Figure 21, before braiding continues. Extra braid rings are used to control this inversion and the location of the braid point. For long shapes of varying cross section, the mandrel traverse speed may need to be varied.

Bifurcated parts can be made by braiding with one leg inside the shed and the other outside, then reversing, then switching leg positions.

The mechanism used to control mandrel traverse is usually custom designed by the user. Test specimens for this contract were made using a precision ballscrew drive capable of highly accurate linear velocity and position control. For the installation at the Watervliet Arsenal, a four-axis robot was used as the mandrel drive. Using this robot, parts can be made having an axis that is bent or twisted.

During wet braiding, fibers pass over the face of the RAR with both a radial and tangential component of motion. A point on a fiber, therefore, will trace out a spiral path on the porous RAR face and will be exposed to flow from several plenums behind the RAR cover plate. The fiber bundle soaks up resin from the film on the RAR face. If the flow rate of resin is high enough, the fiber bundle will be fully wetted by the time it leaves the face of the RAR, if the resin flow rate is too low, the braid will be noticeably dry. If excess resin is pumped, it will end up dripping from the RAR and the mandrel.

For multiple-ply wall buildup, reversals of mandrel traverse direction are needed. The wet braid must be prevented from slipping back on itself during the reversal. Several methods can be used to prevent slippage such as incorporating a ridge or groove in the mandrel, halting mandrel traverse while the braid forms tight hoop wraps, or reaching into the shed with hooks.

For high viscosity mixtures, difficulties in braiding action and fiber wetting may be experienced. If this is the case, the RAR may be heated with hot water flowing through a copper tube embedded in the groove in the plenum plate. The resin viscosity will be lowered; however, the gel time may be significantly shortened.

Any damage that occurs to brittle fibers used in composite products degrades physical properties and causes difficulties during fabrication. For braiding, such damage can cause snags or knots to occur at the RAR, and a matt of broken fibers to build up on the cover plate face. Braider carriers may require special design features to minimize fiber damage. Fiber tension at the carriers must also be carefully selected to minimize fiber damage while allowing proper compaction and resin content on the mandrel.

Several fiber parameters are important to successful wet braiding. Fiber type is initially selected based on structural requirements of the final part. Fiber angle, with respect to the mandrel centerline, is also determined by structural needs. The next step is to select the size of braider and fiber bundle required to achieve full coverage of the mandrel surface through the full wall thickness. Fiber bundle size is affected by the number and diameter of individual filaments and the style and degree of twist. The term "strand" refers to a bundle of filaments that is untwisted. The term "yarn" is a strand that is twisted. Parts made with stranded material will generally yield wider bandwidths, thinner plys, better wetting, and higher mechanical properties than the same material that is twisted into yarn. However, the brittle nature of most composite fibers requires some degree of twist to minimize damage and handling difficulties. The tension on the fiber caused by the braider carriers is another important factor that affects processing and

final fiber content. Fiber manufacturers can supply a range of sizings applied to the fibers which can improve handling and wetout behavior. Any rewinding operations between original source and braider package must minimize fiber fraying and knotting for good braiding behavior and final cured properties. A proper balance of all these parameters is needed to repeatedly make acceptable parts.

Details of fibers used in this study are shown in Table 3. It was found that untwisted roving braided poorly, especially carbon fiber rovings.

Several resin characteristics also affect the quality of wet braiding. Pumps and RAR internal components are selected based on the constituent and mixed resin viscosities to achieve good resin flow, mixing, and distribution. Mixed resin surface tension is also important in slowing draindown of the RAR during pauses in operation. Agents can be added to the resin to reduce entrapped air by reducing surface tension.

The primary resin system used to make specimens was EPON 826/MTHPA/BDMA with a mix ratio of 100/80/1 parts by weight. Room temperature viscosities are summarized in the following table:

Viscosity @ 70°F (CPS)	
EPON 826	8,845
MTHPA	72
Mixture	544
Pot Life	About 6 Hours

Fiber wetting is affected by all of the above fiber and resin parameters. Factors that promote good wetting include low bundle twist, low viscosity, and low surface tension. Factors that promote good braiding are high bundle twist, low viscosity, and high surface tension. A balance must be reached among these conflicting requirements with fiber sizings or resin additives selected if needed.

Once a part is braided, these same factors also influence part quality. Low viscosity resins will drip and drain off a part until the resin gels, so the part is rotated while curing or a bag is applied. During heat cure, any entrained moisture will result in bubbles appearing in the finished part. Fiber/resin reactions may occur at elevated cure temperatures that may affect the final part quality.

An oven was constructed with provision for a rotisserie to rotate parts about a horizontal axis. A gatling gun style fixture was used to load mandrels into the rotisserie as soon as they were removed from the wet braiding station. Parts were rotated continuously from room temperature through the staging cycle. Some parts were allowed to cool to room temperature after staging, then reheated without rotation to the cure temperature.

One problem noted when using Kevlar with the Epon 826/MTHPA/BDMA resin system was an apparent liquefying process that occurred as previously staged parts were reheated to the cure temperature. The parts removed from the oven after curing and cooling without rotation had drops of resin "frozen" along the bottom side of each specimen.

9. Test Specimens

Figure 22 shows the details of specimen fabrication.

Parts were made on a 64 Carrier braider over a one-inch mandrel at a $\pm 45^{\circ}$ fiber angle. Fibers included S-glass yarn and slightly twisted rovings of S-glass, Kevlar, and graphite. Three types of specimens were made for mechanical testing: thin wall, long gage length; thin wall, short gage length; and thick wall, short gage length. Six specimens of each type were made; properties to be evaluated include tensile and shear modulus and strength. The braider was configured for a standard 2-over, 2-under biaxial pattern.

Type	Gage Length	Wall Thickness
Thin/Long	5.5 ± 0.5"	<.050"
Thin/Short	2.5 - 3.0"	<.050"
Thick/Short	2.5 - 3.0"	.110 - .140"

Triaxial tubes without grips were also made, using 750 yield glass roving for braided fibers and 1250 yield glass roving for warps. No difficulties in fiber handling or wetting were experienced.

Anodized aluminum mandrels were used, having a taper of .003" over their three foot length and coated with release agent in order to aid release after cure. Three specimens were made per mandrel. Reversals of mandrel direction were made after a pause to build up hoop wraps. The mandrel drive was programmed to reciprocate to build up enough plys for the required wall thickness. Grip segments were then built up, with spacer tubes inserted over the gage lengths so that the braid could walk over to the next grip section, as shown in Figure 23. The spacer tubes were removed after cure. Removal of specimens from the mandrels was aided by a cold soak in a freezer, then torquing or tapping the mandrel.

Data from burnoff tests on glass specimens and acid digestion tests on Kevlar and carbon specimens is presented in Table 4. It should be noted that the results for carbon reflect excessive coverage of the mandrel due to the heavy bandwidth of untwisted 12K material. Dry trial braiding resulted in a noticeably spongy ply buildup. A typical polished cross-section was shown in Figure 7, showing good wetting of bundles. Appendix B lists details of test specimens which were wet braided for this program.

Cleanup consists of parting the shed and removing the RAR from the braider. The RAR is disassembled and the components are cleaned with the

appropriate solvent. Experience has shown that after several dozen uses, there is no tendency of permanent blockage of the cover plate holes.

10. Conclusions

The work completed under this SBIR Phase II contract resulted in a significant advancement in composite braiding technology. The following conclusions are made about the Phase II results:

1. The resin applicator ring was successfully scaled up and demonstrated in a series of tests with S2 glass yarn, S2 glass roving, Kevlar 49 roving, and carbon fiber roving. A 450 mm bore RAR system was delivered to the Watervliet Arsenal and successfully operated by Watervliet personnel. Operation in biaxial, triaxial, and bi-directional braiding modes were verified by a series of 18 test runs.

2. Resin applicator ring components can be fabricated at a reasonable cost. It appears feasible to build rings of any size desired (e.g., up to four foot dia.) for the largest available braiders, the Mossberg 144 carrier or the Babcock 160 carrier. Ring set up, operation, and clean-up procedures have been developed.

3. Relatively high internal pressures caused repeated seal failures in the first "scaled-up" RAR, a 200 mm bore unit for the 64 carrier braider. Leakage problems were corrected by revision to the face seal clamping system.

4. A computer numerically controlled (CNC) resin pumping system was developed for use with the RAR system. The system consists of precision gear pumps driven by computer-controlled servomotors. The pumping system proved capable of metering epoxy resin and curing agent with an accuracy of 1% or better under typical RAR pressure and flow rate conditions.

5. Of the four fibers tested, S2 glass yarn proved to be the easiest and carbon fiber roving the most difficult. It was necessary to impart a moderate twist in roving products in order to achieve acceptable braiding behavior. U.S. Composites developed modifications to the standard Mossberg carrier under a separate program; fiber handling problems have been minimized as a result.

6. Based on the test experience gained with two epoxy systems, Epon 826/MTHPA/BDMA and Dow Tactix (TM) 138/H41, we conclude that any resin suitable for wet filament winding will perform well in the RAR system. The following properties are suggested for alternate resin systems:

Mixed viscosity: 500-1,000 cps is optimum; 2,000 cps maximum.
Pot Life: One hour minimum at the ring operating temperature. Surface Tension: .03-.04 N/m

7. In most tests, the fiber volume fraction was within $\pm$ 3% of the value predicted by the BRAID program. The fiber volume fractions ranged from 56.8 to 63.9% (excluding the 12k carbon case in which fiber "jamming" was experienced). Structural composites typically require fiber volume fraction of 50 to 70%. The measured void contents ranged from 1.7 to 3.7%, a major improvement over existing resin application techniques.

8. The RAR concept of wetting fibers passing over a porous plate can be adapted to other processes such as filament winding or co-pregging in tape laying processes. The orientation of the porous plate can be varied to suit the process.

11. Recommendations for Future Work

This Phase II effort demonstrated the viability of a production scale composite braiding system with computer control and the resin applicator ring system. Additional work is recommended which will increase the range of application for braided composites, optimize the process to meet specific application performance requirements, and overcome certain limitations inherent in existing braiding machinery. Our recommendations for future work are as follows:

1. Develop Simple Compaction Procedures

The goal of this work would be to develop simple methods of increasing the fiber volume fraction and decreasing the void content of wet-braided parts. Aerospace composites made with prepreg materials typically require fiber volume fraction of 60 to 70% and void contents of 2% or less. Some specifications call for less than 1% voids. While the RAR system has been shown to be capable of producing high-quality composites, parts cured on the mandrel without compaction do not consistently meet the specifications for autoclave cured prepreg composites. Because the RAR system comes close to meeting this level of performance with no compaction whatsoever, it is likely that a low cost approach such as resin deaeration and shrink tape wrapping prior to cure can increase performance to its highest level without losing the substantial cost advantage. Examples of Army programs which might directly benefit from this development include the SMAW Launch Tube (USA MICOM), the Tri-Arch Bridge Truss Tube (Army Belvoir R, D, & E Center), and the Lightweight Howitzer (ARDEC).

2. Test the RAR System with High Performance Resins

The Phase II research concentrated on development and demonstration of composite braiding with the RAR system. A standard filament winding type epoxy resin was used for most of the test runs. However, many Army applications will require higher temperature capabilities or other special requirements. Resin suppliers have recently introduced new resin systems with improved hot/wet capabilities, greater toughness, and improved processing characteristics. One example of an advanced resin system is the Dow XU71787.03L polycyanate resin which has a dry Tg of 225°C (437°F) and shows minimal moisture absorption. Bismaleimide and polyimide resins can extend the service temperatures range to 300°C and beyond. Successful testing of the RAR system with these advanced resins will enable high-temperature components such as conventional and electro-magnetic gun tubes to be economically fabricated by braiding.

3. Develop a Modern Braiding Machine

The tubular braiders presently used in composite braiding are standard textile machines adapted for use with high-performance fibers. The basic design of the braiders has not changed since the turn of the century. Modern machine design principles could be applied to design a new, high-speed braider with greatly enhanced performance. The benefits of this development would be significant:

- The diameter (or perimeter) of parts that could be braided would be increased.
- Higher operating speeds would further reduce unit costs.
- New carrier designs would enable the use of much larger fiber packages--standard braider packages can only accept 100 to 125 grams of carbon fiber. Larger packages would reduce the portion of time spent reloading the braider.
- The carrier tensioning system could be optimized for use with high-modulus fibers, including ceramics. The standard Mossberg carriers must be extensively modified to provide acceptable performance with graphite and ceramic fibers, and there is still a need for improvement.

4. Adapt the RAR Concept to Other Composite Fabrication Technologies

The Phase I test apparatus was a rudimentary filament winder; the porous plate experiments showed that the RAR concept would wet fibers being wound. An RAR system specifically designed for filament winding might enhance the capabilities of computer controlled

filament winders by introducing software control over the resin application. Present bath-type impregnators cannot be controlled, so resin content and wetting are affected by changes in fiber speed and tension. Filament winders that are fabricating complex geometry shapes will experience changes in fiber tension and speed.

12. Patent Rights Assignment

The technology described in this final report is covered by U.S. Patent 4,494,436. Patents are awarded or pending in thirteen other countries. Upon award of the SBIR Phase II contract, U.S. Composites Corp. assigned to the U.S. Government a non-exclusive, non-transferrable, irrevocable, paid-up license to practice the invention in facilities owned by the U.S. Government. In addition, E.I. du Pont de Nemours & Company, Inc., Wilmington, Delaware has been assigned a license to the technology under a Phase III commercialization agreement.

13. Acknowledgment

The authors wish to express their gratitude to Mr. Noel Tessier of the Army Materials Technology Laboratory for his invaluable guidance and support.

14. Biographies

A. HUGO KRUESI founded U.S. Composites Corp. and serves as President. He has been awarded U.S. and international patents on the resin applicator ring system. He graduated from Rutgers University with a BSME and has taken composite courses at RPI and Yale.

GREGORY H. HASKO is the chief engineer at U.S. Composites. He was formerly employed as a senior engineer at Combustion Engineering and the Hamilton Standard division of UTC. Mr. Hasko received his BS and MSME degrees from Rensselaer Polytechnic Institute, and is a registered professional engineer.

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Drawings:

14. E-RAR450-0037: "Assembly, RAR, 566 mm Dia"

15. E-RAR450-0039: "Assembly, RAR Support"

16. D-RAR450-0040: "Assembly-RAR, 330 mm Dia"

17. D-RAR450-0041: "Assembly-Reversing Ring"

18. D-RAR450-0043: "Assembly-Resin Delivery"

OPERATION AND MAINTENANCE

Guidelines for Resin Applicator Ring System

I Components

A. Resin Applicator Ring (RAR):

1. Aluminum plenum plate with clamp assemblies

2. Foam divider strips

3. Flow restrictor pins

4. O-Ring

5. Inner and outer cover plate seals

Clean with denatured alcohol, do not use acetone.

6. Filter paper:

Low porosity E-D950-25,.007" thick
High porosity E-D909-20,.006" thick

7. Cover plate:

Two supplied, each with 10,800 holes of .015" mean diameter.

8. Disposable mixers:

Low viscosity, low flow rate 3/8" dia x 6 3/4" long
High viscosity, high flow rate 1/2" dia x 9 1/2" long

9. Mixer pressure gage

10. Mixer tube

11. Mixer block

12. Clamps

13. Relief valve:

Clean with denatured alcohol, do not use acetone.

B. Pumps: Nichols-Zenith, 1.75 ml/rev chamber size

Do not run dry, clean with denatured alcohol or acetone. Store with oil in chamber. Refer to Nichols-Zenith maintenance guide.

C. Tanks: 80 psi max

1. Safety relief valve: adjustable from 20 to 50 psi Screwing cap all the way down increases release pressure.

2. Regulator: Outlet pressure range = 5 to 125 psi, maximum inlet pressure = 300 psi. Unscrewing the T-Handle reduces the pressure. Approach the desired pressure from below.

3. Filters

4. Tubing

D. Reversing Ring

Adjust so that fibers are held against RAR cover plate when braiding away from braider, but no fibers are pinched between RAR and reversing ring.

E. Pump Motors

F. Reference Drawings

RAR450 ASS'Y	E-RAR450-0037
RAR450 ARMS	E-RAR450-0039
RAR450 REV RING	D-RAR450-0041
RAR450 RESIN SUPPLY	D-RAR450-0043

II Component Selection

A. Pins

A knowledge of mixed resin viscosity and resin flow rate is needed. Pins are sized with notches in order to vary flow distribution around the ring. Flow distribution is affected by flow pressure, which is a function of flow rate, viscosity, and flow restriction. For the RAR 450, 36 pins are used.

Pins can be initially selected by multiplying the maximum operating flow rate, in ml/min, by the mixed resin viscosity in centipoise. Refer to the following table

Flow Rate x Viscosity (ml/min x Centipoise

Low End	High End	Pin Number	Notch Size
50,000	100,000	-4	.042
100,000	200,000	-5	.050
200,000	400,000	-6	.058
400,000	800,000	-7	.066

For (flow rate x viscosity) products outside this table, other pins would have to be ordered. In general, the largest notch size that results in good resin distribution should be used.

B. Filter Paper

For fluids of mixed viscosity up to 1000 cps, use the lower porosity grade, E-D 950-25. Above this viscosity, use the higher porosity E-D 909-20.

C. Pumps

The original pumps have a 1.752 ml/rev chamber size. Do not exceed 250 rpm for any operating condition. Normal operation should not exceed 100 rpm for extended running while braiding. If flow rates higher than 100 x 1.752, or 175 ml/min per pump are anticipated, larger pumps should be ordered. Spare parts and disassembly information are obtained from the pump manufacturer.

Pump performance is affected by fluid viscosity, operating speed, and pressure differential between inlet and outlet. Volumetric flow may be reduced from the theoretical (chamber size x rpm) if fluid viscosity or rpm are too low or the pressure differential is too high. Performance may also change over time due to wear. Therefore, the flow rate should be checked periodically and when trying new resins with a throttle valve downstream to create typical back pressure, and tanks pressurized.

A trial wet run is recommended, noting mixer pressure, flow distribution, leak checking, etc. for the range of anticipated flow rates, before doing wet braiding.

D. Pump Motors

Motor shaft torque at 100 rpm is 40 in-lb. Torque required to turn the pumps is a function of gear ratio, pump size, pump speed, fluid viscosity, and differential pressure between the pump inlet and outlet. Pump shaft torque should be calculated for a given set of operating conditions. If this value exceeds the motor rating, the pump drive gear and micarta gear should be changed in order to reduce the load on the motor. This will also necessitate a software change. Consult U.S. Composites if this is needed.

The maximum allowable operating speed limit should also be calculated, based on maximum allowable motor torque, for reference when initially filling the tubing leading to the mixer block.

Pump torque is calculated as follows, for 1.725 ml/rev chamber size:

Pump Torque = Hydraulic Torque + Viscous Torque

$$\text{(in-lb)} = \left[\frac{(1.752)(\text{Pressure Difference, psi})}{103}\right] +$$

$$\left[(6.28 \times 10^{-3}) \times (\text{Fluid Viscosity, Poise}) \times (\text{Pump Speed, rpm})\right]$$

Example: Epon 826, 8845 cps

$$\text{max RPM} = \frac{40}{(6.28 \times 10^{-3})(88.45)} = 72$$

For other pump sizes, consult the pump manufacturer.

E. Braider

Drip pans should be installed under the RAR and under the full mandrel traverse zone.

F. Pressure Relief Setting: Procedure

1. Determine by test normal flow pressure for a given resin system, flow rate, and RAR setup (mixer, pins, filter paper, etc.) at the mixing block pressure gage.

2. Set cracking pressure of valve on a bench test. One method is to fill a line with water at the valve inlet, monitor line pressure while applying pressure with a syringe, and adjust cracking pressure to be about 20 percent above normal operating pressure. Lock adjustment screw with jamb nut.

3. Install valve next to pressure gage on the mixing block with a "T" fitting.

III Assembly:

A. RAR

1. Rest plenum plate on wood blocks on a horizontal surface so that clamps are free. Snug tighten any loose clamp bracket bolts, leave clamps all the way open.

2. Inspect for any particles or resin residue at the top surface, pin holes, inner and outer diameters, and grooves. Clean surfaces with acetone or denatured alcohol.

3. Inspect pins for particles or resin residue especially in notches. After cleaning, drop into holes in plenum plate.

4. Slip O-Ring into position at the outside diameter of the distribution channel in plenum plate. Using a tongue depressor, work seal into groove so that the outer diameter of seal is flush with outer diameter of channel, no deeper.

5. Install inner and outer cover plate seals, being careful to avoid twists and kinks.

6. Install foam divider strips. Install filter paper in cover plate, being careful not to kink. Set clamps to proper compression.

7. With a uniform motion all around, lower cover plate into position. Check for proper seating, then close clamps, alternating across the diameter.

8. Trim a disposable mixing element halfway down the cone at the entry end. Slide into proper size housing and attach mixing block at entry end. Attach pressure gage and relief valve.

9. Position RAR on mounting arms on braider, and close toggle clamps. Check for looseness.

10. Attach mixer assembly to RAR, and attach lines to mixer.

11. Check all line connections for tightness. Check filters.

12. Braider fibers may be tied off into a pigtail.

13. Position reversing ring so that fibers are flat across RAR surface, but not pinched between rings.

14. Clean oil from pump chambers. Verify freedom from binding by turning by hand. Mount on saddles and engage drive gears.

15. Install gear guard.

RAR Assembly Checklist

______ Flow Restrictor Pins

______ O-Ring

______ Inner Face Seal

______ Outer Face Seal

______ Foam Divider Strips

______ Filter Paper

______ Static Mixing Element

______ Pressure Gage

______ Filters on Tank Exit Lines

______ RAR Relief Valve

______ Pumps Free to Turn

______ RAR Mounted

______ Lines Connected

______ Fibers Tied

______ Reversing Ring Positioned

______ Tanks Filled and Pressurized

IV Operation

Note: It is recommended that the Material Safety Data Sheets be consulted for the particular resins used, and that personnel wear the proper safety equipment (gloves, goggles, respirators, etc.) when using the RAR.

A. Set tank safety relief valve to 50 psi. Pour resin and catalyst into proper tanks.

B. Pressurize tanks, preferably with dry filtered nitrogen, to 10 psi.

C. Observe fluid in lines between tanks and pumps. If air remains in lines and fluid does not reach pumps, the pumps may be run slowly (about 10 rpm) to allow air to pass through.

D. Run each pump separately to advance fluid up to mixer head. Observe limits on pump speed versus fluid viscosity.

E. Set proper speed ratio and total flow rates for the resin and mandrel selected. Observe ring filling behavior at front of cover plate. Observe mixer pressure gage.

F. When the RAR is full, check for leakage in lines, fittings, and around seals. Do not exceed flow rates determined in pin selection step (part II A). If pressure becomes excessive, shut off pumps and double check the set up. Caution: Excess pressure can cause damage to hardware and personnel.

G. Proceed with braiding. If braiding is stopped for an extended period of time, either in the process of braiding one part or when changing mandrels, pumps may be shut off. The RAR may drain down during this time, so the pumps should be run until any air in the ring is pushed out before braiding resumes.

Pauses in pumping should be limited in duration to less than the gel time of the resin system being used. Cleanup should begin with this time limit in mind when braiding is completed. Caution: Leaving mixed resin in the RAR too long may lead to excessive flow pressure, poor braiding due to gelling, overheating from resin exotherm, or bonding together of RAR components.

H. During operation, a fault condition may arise which can cause erroneous resin mixing and flow and lead to damage of hardware. If the flow of the low viscosity fluid of a two component resin system stops due to leakage, pump malfunction, control failure,

etc., the total flow rate will be reduced. However, the viscosity of the fluid entering the RAR will increase, so flow pressure may actually increase. If this situation arises, resin mix ratio will be thrown off. Operations should be halted and cleanup initiated. The pressure relief valve is intended to relieve this overpressure condition before damage occurs to other components of the system.

V Cleanup -- When Pumps are Shut Off and Tank Pressure is Released:

A. First move reversing ring aside, then part fibers for access to the RAR. Disconnect lines into mixing head, disconnect mixer assembly from RAR, remove RAR from mounts, and move to cleanup area. <u>Caution</u>: Opening lines if mixer gage still shows pressure can cause resin to spurt out. This can be hazardous to health. All personnel in the vicinity must wear protective clothing and splash-proof eyewear.

B. RAR

1. Open clamps around ring.

2. Remove cover plate, discard filter paper and foam dividers. Excess resin and resin saturated components should be cured prior to disposal.

3. Remove seals and clean with denatured alcohol. Do not use acetone.

4. Remove flow restrictor pins and place in solvent. After cleaning, place in labeled container.

5. Clean cover plate and plenum plate by placing in a shallow bath of denatured alcohol or acetone, force solvent through cover plate holes with a bristle brush. Do not use chlorinated solvents.

WARNING: THESE SOLVENTS ARE FLAMMABLE! FOLLOW ALL APPLICABLE SAFETY PROCEDURES.

C. Mixer

1. Disassemble mixer head and tube. Remove and discard static mixing tube.

2. Clean head and tube with alcohol or acetone.

D. Pumps

1. Relieve pressure from tanks.

   Caution: Opening a pressurized line can be hazardous to health, as in step V A.

2. Remove from mounting saddles.

3. Fill pump with acetone, rotating drive gear by hand. Allow to stand, periodically flushing with fresh solvent.

4. Fill pump with lubricating oil and rotate drive gear so that internal components get coated.

E. Tanks and Lines

1. Swab out with denatured alcohol or acetone.

F. Reversing Ring

1. Clean any resin with denatured alcohol or acetone.

RAR Cleanup Checklist

_____ Release Tank Pressure

_____ Check Mixer Pressure Gage

_____ Reversing Ring

_____ Part Fibers and tie off

_____ Lines

_____ Tanks

_____ Pumps

_____ Cover Plate

_____ Pins

_____ Plenum Plate

_____ Seals

_____ Clamps

_____ Mixer

_____ Braid Ring

VI Troubleshooting

Symptoms	Possible Cause
1. Bubbles traveling in line between tank and pumps.	o Reservoir drained. o Entrained air in resin.
2. Line between tank and pump full, but bubbles in stream at pump outlet.	o Loose fitting allows air in. o Loose pump seals allow air in. o Clogged filter causes air suction even though fittings are tight. Many epoxy resins must be heated to prevent crystallization.
3. Pump runs slower than control setting.	o Viscosity/pump speed/ motor torque limits exceeded.
4. RAR face shows zones of high viscosity and low viscosity fluid flow during steady operation.	o Static mixing element not installed.
5. Leakage at cover plate seals.	o Flow rate/viscosity limits exceeded. o Seals installed incorrectly. o Clamps not set properly.
6. Poor resin distribution.	o Wrong pins used or omitted. o Filter paper omitted.
7. High flow pressure.	o Pin ports clogged.

VII RAR SYSTEM COMPONENT SOURCES
For Operation and Maintenance Section

1. Foam for Divider Strips

   Scottfoam
   1500 E. Second Street
   Eddystone, PA 19013
   800-222-2470

   "Scottfelt" Polyester Polyurethane
   Firmness 4, Grade 900Z
   1/8" Thickness
   Open Cell

2. Filter Paper

   Filtration Sciences Corp.
   Eaton-Dikeman Division
   P.O. Box A
   Mount Holly Springs, PA 17065
   717-486-3438

   1. "ED 950-25"
      Thickness = .007"
      Rapidity = 12 ml/min

   2. "ED 909-20"
      Thickness = .006"
      Rapidity = 60 ml/min

3. Disposable Mixing Elements

   Liquid Control Corp.
   7576 Freedom Ave. N.W.
   P.O. Box 2747
   North Canton, OH 44720
   216-494-1313

   "Posimixer 60/40"

   1. 1/4" ID
      P/N 60/0053-A/50

   2. 3/8" ID
      P/N 60/0052-A/50

4. Pumps

   Nichols-Zenith Division
   Parker Hannifin Corp.
   48 Woerd Ave.
   P.O. Box 71
   Waltham, MA 02254
   617-894-0650

   Precision Gear Pump

   BPB-4391-1.752 cc/rev
   Micarta Drive Gear, 42 Teeth
   for 1:1 ratio with motor.

5. Pump Motors

   Cincinnati Controls
   6580 Corporate Drive
   Cincinnati, OH 45242
   513-530-0044

   Westamp #MT235 Servomotor

6. Face Seals Conap, Inc. 1405 Buffalo St. Olean, NY 14760	TU-600" Conathane" parts A&B (60 durometer when cured)
7. O-Ring Apple Rubber Products 310 Erie Street Lancaster, NY 14086 716-684-6560	21.6" x .210" 70 Duro EP Apple Rubber
8. Tanks Utensco P.O. Box 710 Port Washington, NY 11050 516-883-7300	PTA-3 PTA-6 80psi max 100°C
9. Cover Plate Clamps Southco, Inc. Concordville, PA 19331 215-459-4000	A1-10-501-10 Draw Latch, Adjustable
10. RAR Clamps Carr-Lane Manufacturing Co. 4200 Carr Lane Ct. P.O. Box 13149 St. Louis, MO 63119 314-647-6200	CL-251-PA Toggle Clamp
11. Auto Relief Valve Special Plastic Systems 914 Westminster Avenue Alhambra, CA 91803 800-432-4422	FC-MPR-25-1 15 to 75 psi

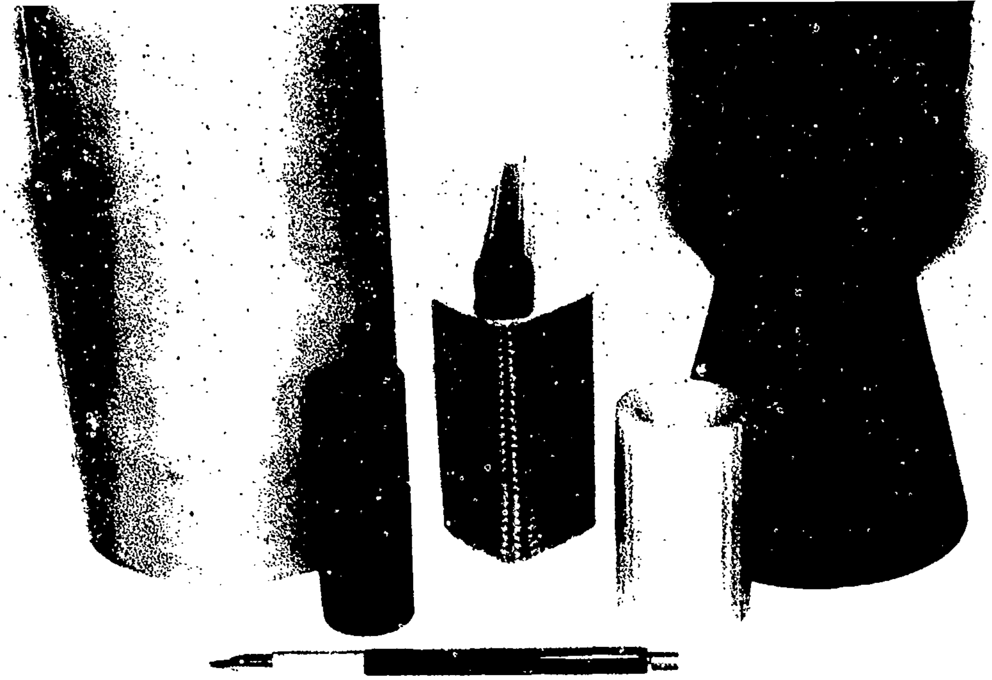


Figure 1 Examples of Carbon, Kevlar, and Glass Fiber Braided Composites

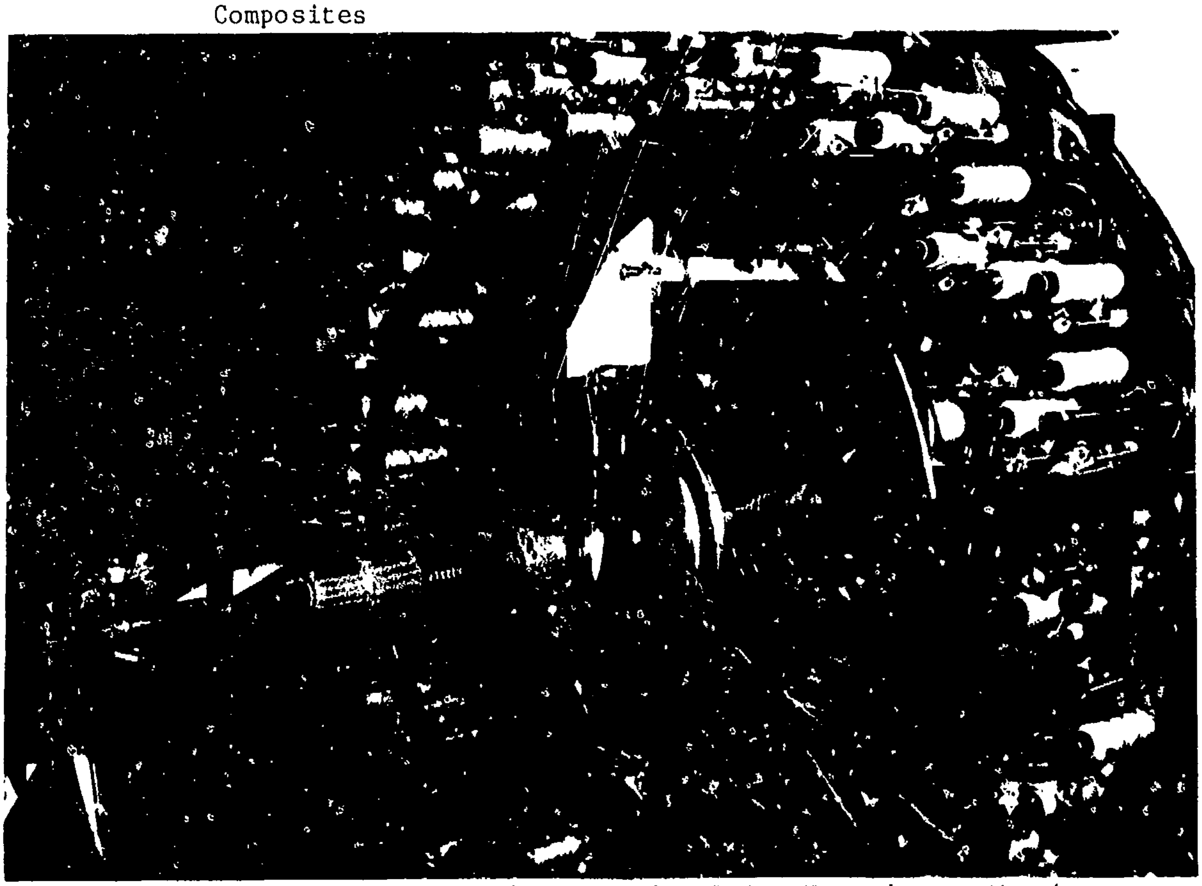


Figure 3 Prototype Resin Applicator Ring Being Tested on a Mossberg 64-Carrier Braider

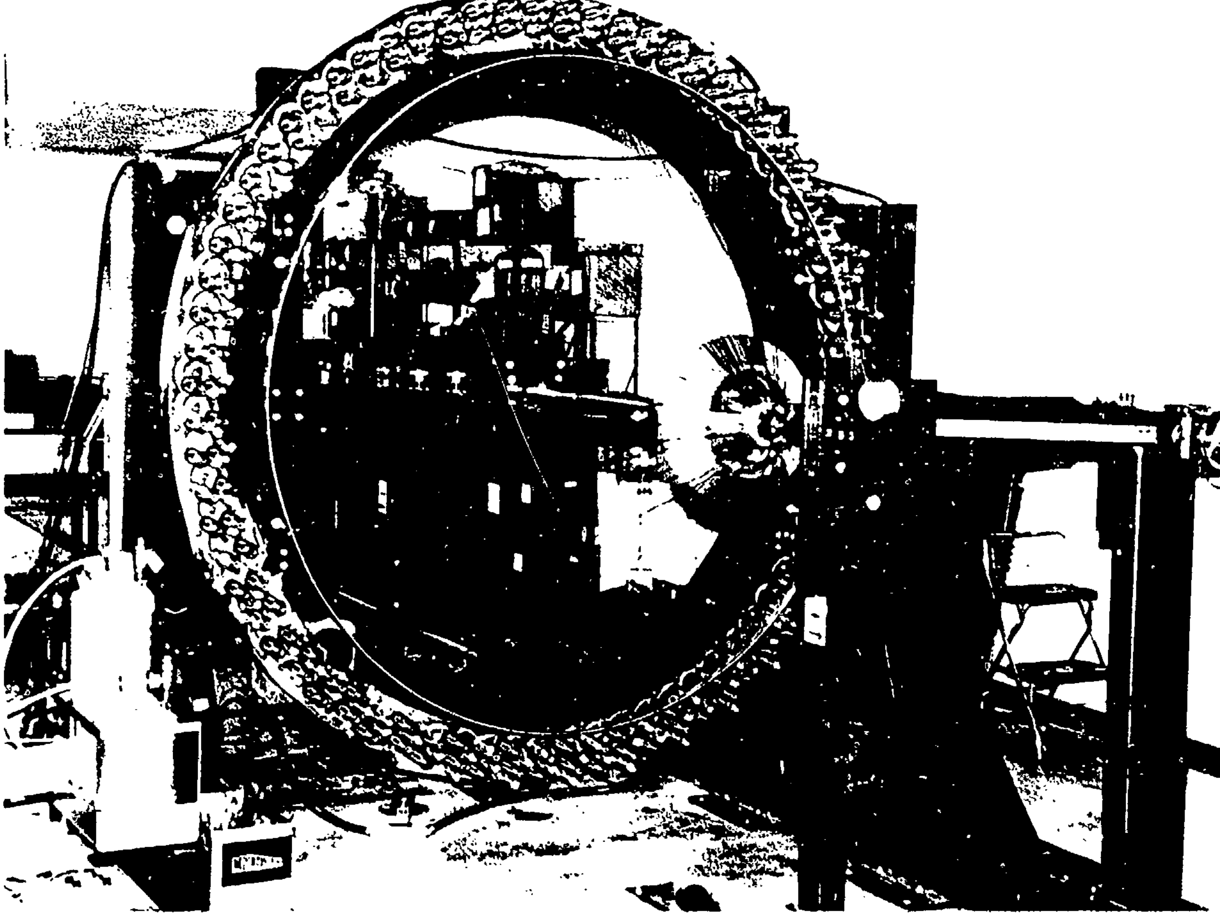
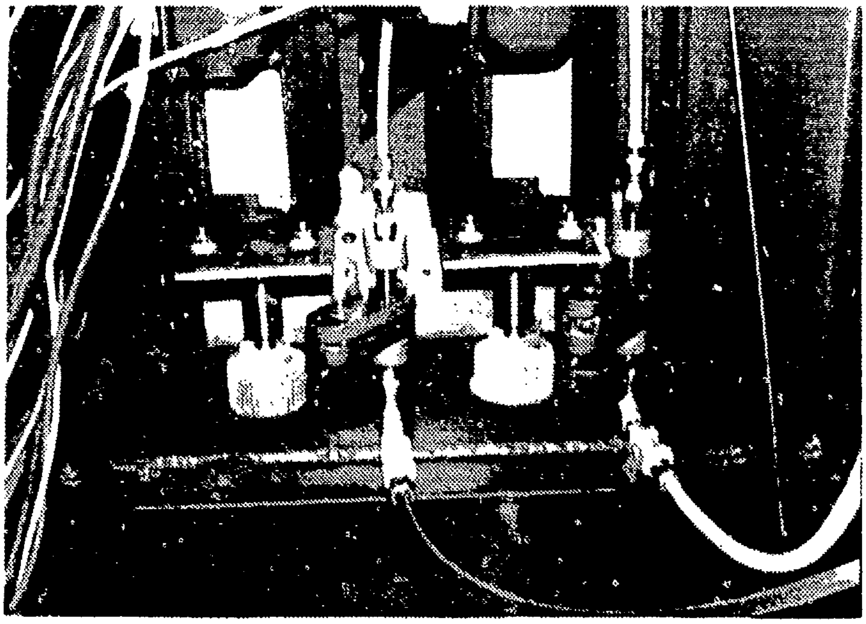


Figure [illegible]. 144 Carrier [illegible] Braider with Resin Applicator Ring and [illegible]-Axis Computer Numerical Control



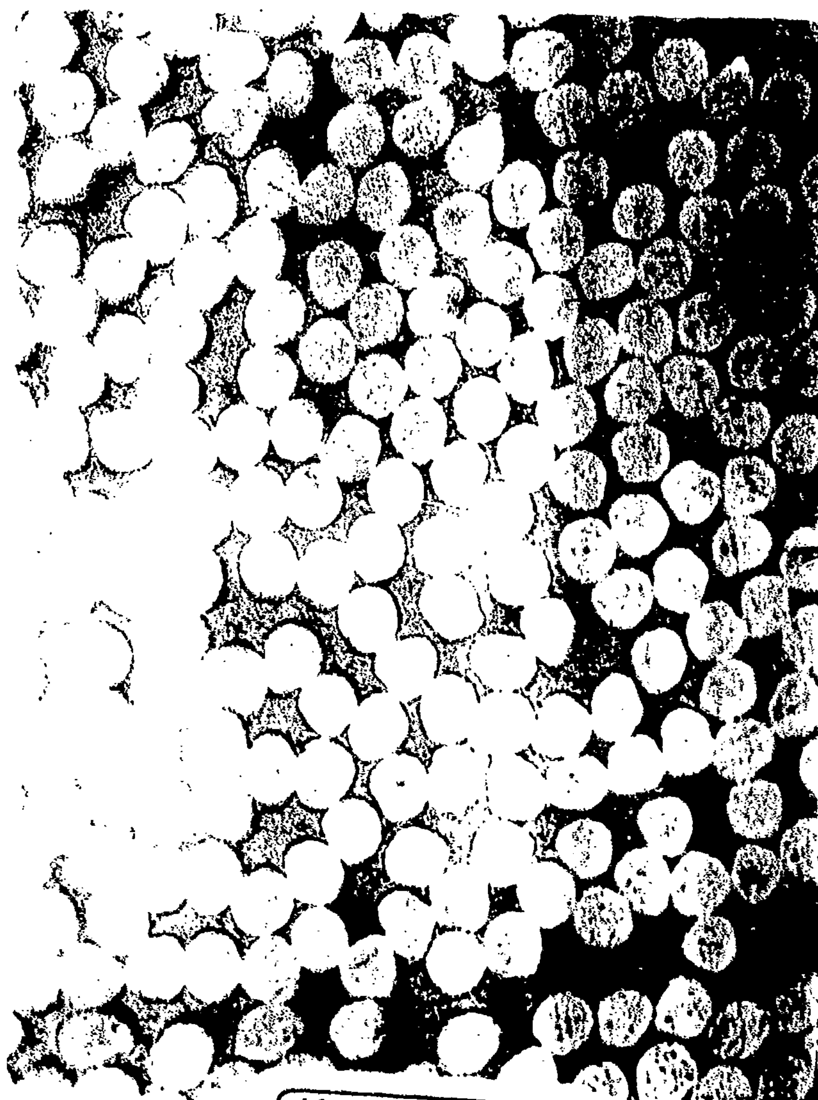


Figure 6 Microphotograph of Wet-Braided Kevlar/Epoxy (404 X)

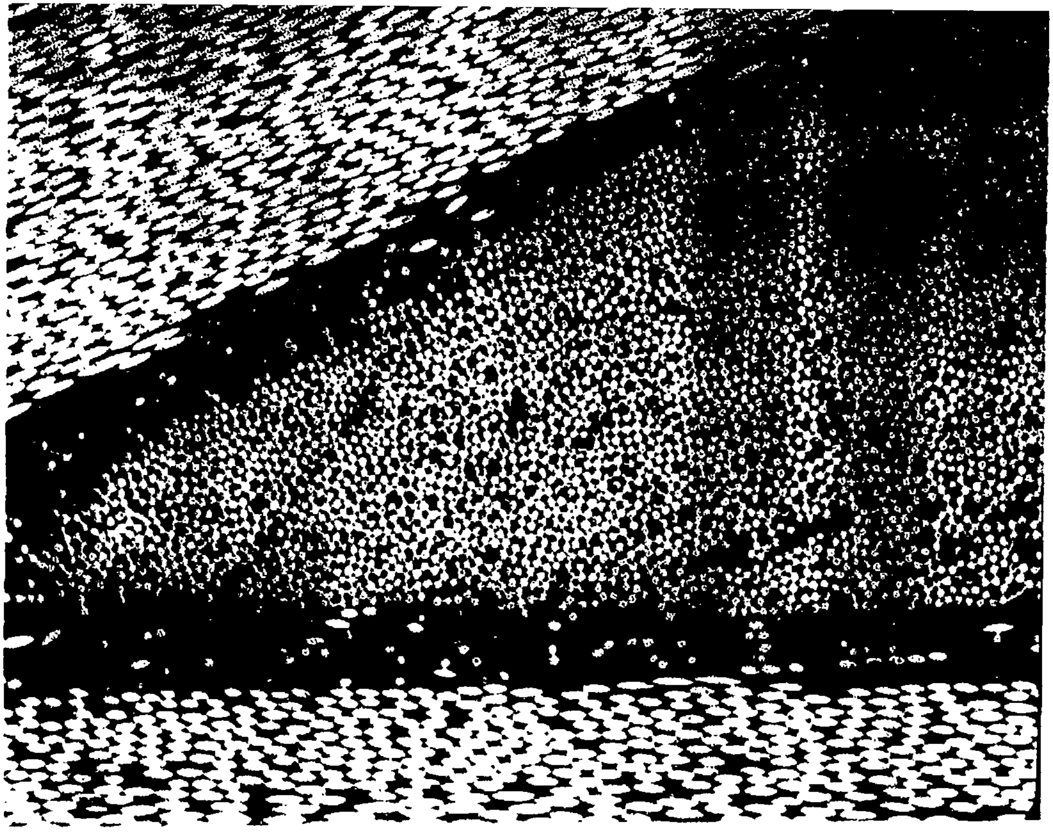
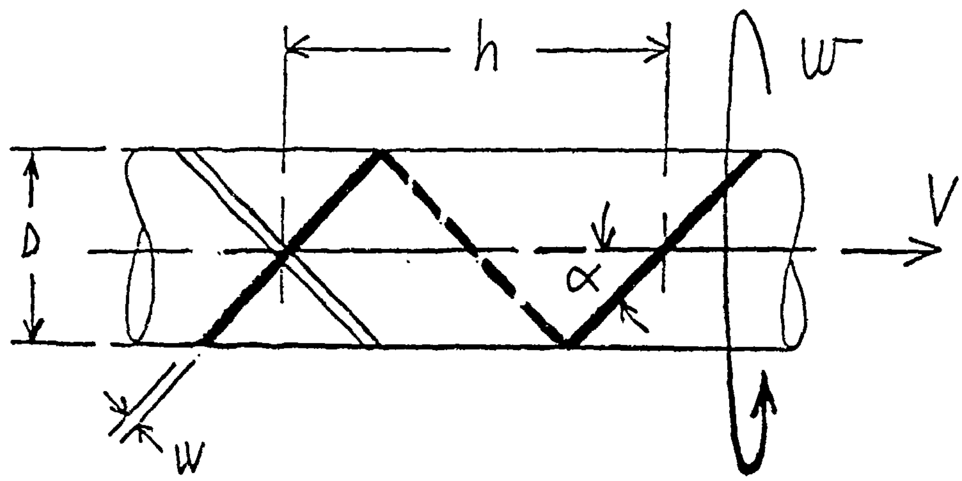


Figure 7a Wet-Braided Carbon/Epoxy Showing Elliptical Fiber Bundles Surrounded by Resin-Rich Areas (150x)

Figure 7b Circular Shaped Voids in Resin Rich Areas of Wet Braided Part (50x)



D = Part Diameter

N = Number of Spools on Braider

V = Mandrel Velocity

h = Fiber Wrap Pitch Length

w = Fiber band width

α = Fiber Angle

ω = Fiber Carrier Rotational Speed in RPM

Braiding Notation

Figure 8

Sample BRAID Program Output

BRAID - COMPUTE PART COVERAGE FROM BRAID ANGLE AND PART DIAMETER

Developed by
U.S. Composites Corp.
Rensselaer Technology Park
Troy, New York 12180
(518)-283-8700

TRIAXIAL Example

```
Part is  2.750 inches in diameter by  36.00 inches long ( 69.85 mm by   0.91 m long)
Braid angle is 0, 55.00 degrees; Construction =  11.90 picks/inch (  4.69 picks/cm)
Bias fibers: S2 Glass Roving,  750.00 yds/lb,  1 end(s).  Assumed Aspect Ratio =   7.00
Warp fibers: Carbon Fiber    , 2470.00 yds/lb,  1end(s).  Assumed Aspect Ratio =   6.00
Assumed Bundle Fiber Volume Fraction = 0.800
Run on a 144 carrier braider operating at 160.00 picks/minute
        Results for ply number  1:
Bias Fiber Coverage =  99.95 %     Average fiber volume fraction = 0.508
Ply thickness = 0.0357 inches (  0.91 mm)     Mandrel feed rate =    13.44 in/min ( 0.341 m/min)
Weight bias fiber/ply =    0.3355 lb     Bias fiber width =  0.068 in (1.71985 mm)
Weight warp fiber/ply =     0.029 lb     Warp fiber width = 0.041 in (1.04870 mm)
Thickness of equivalent zero degree ply = 0.0047 inches ( 0.119 mm)
Thickness of equivalent + or - 55.00 degree plies =  0.0041 inches( 0.104 mm)
                                                   % Excess Resin
Resin Flow Rate to Produce                   0%     10%    20%    30%    40%
Average Fiber Volume Fraction, ml/min =  24.85  27.34  29.82  32.31  34.79
```

BIAXIAL Example

```
Part is  2.750 inches in diameter by  36.00 inches long ( 69.85 mm by   0.91 m long)
Braid angle is  55.00 degrees; Construction =  11.90 picks/inch (  4.69 picks/cm)
Bias fibers: Kevlar 49       ,  980.00 yds/lb,  1 end(s).  Assumed Aspect Ratio =   6.00
Assumed Bundle Fiber Volume Fraction = 0.800
Run on a 144 carrier braider operating at 160.00 picks/minute
        Results for ply number  1:
Bias Fiber Coverage = 100.15 %     Average fiber volume fraction = 0.653
Ply thickness = 0.0240 inches (  0.61 mm)     Mandrel feed rate =    13.44 in/min ( 0.341 m/min)
Weight bias fiber/ply =    0.2569 lb     Bias fiber width =  0.072 in (1.83254 mm)
Thickness of equivalent zero degree ply = 0.0000 inches ( 0.000 mm)
Thickness of equivalent + or - 55.00 degree plies =  0.0060 inches( 0.153 mm)
                                                   % Excess Resin
Resin Flow Rate to Produce                   0%     10%    20%    30%    40%
Average Fiber Volume Fraction, ml/min =  16.07  17.68  19.28  20.89  22.50
```

```
Resin Type: Tactix 123/H31
Percent Flow Rates:  83.50% Resin Pump,  16.50% Catalyst Pump
Cure Schedule:
        Ramp: 1.000hr  to 176 degrees F
        Soak: 1.000hr  to 176 degrees F
        Ramp: 1.000hr  to 302 degrees F
        Soak: 2.000hr  to 302 degrees F
        Ramp: 2.000hr  to  60 degrees F
```

Figure 9

Delivered Volume vs Pump Revolutions
".160" cc/rev Size, MTHPA
No Pressure Differential

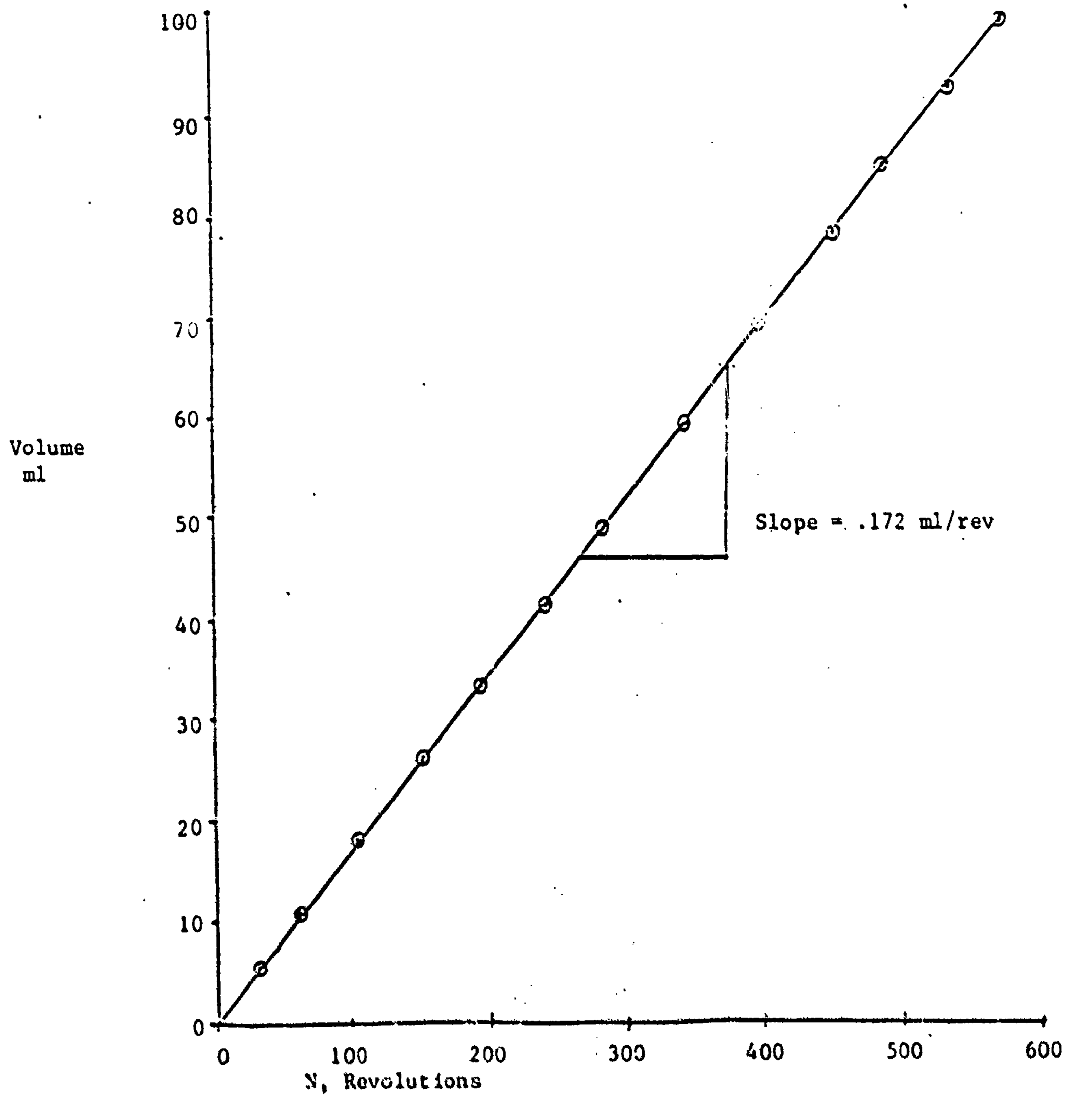


Figure 10

Flow Rate vs Pressure Differential
.172 cc/rev Pump
MTHPA

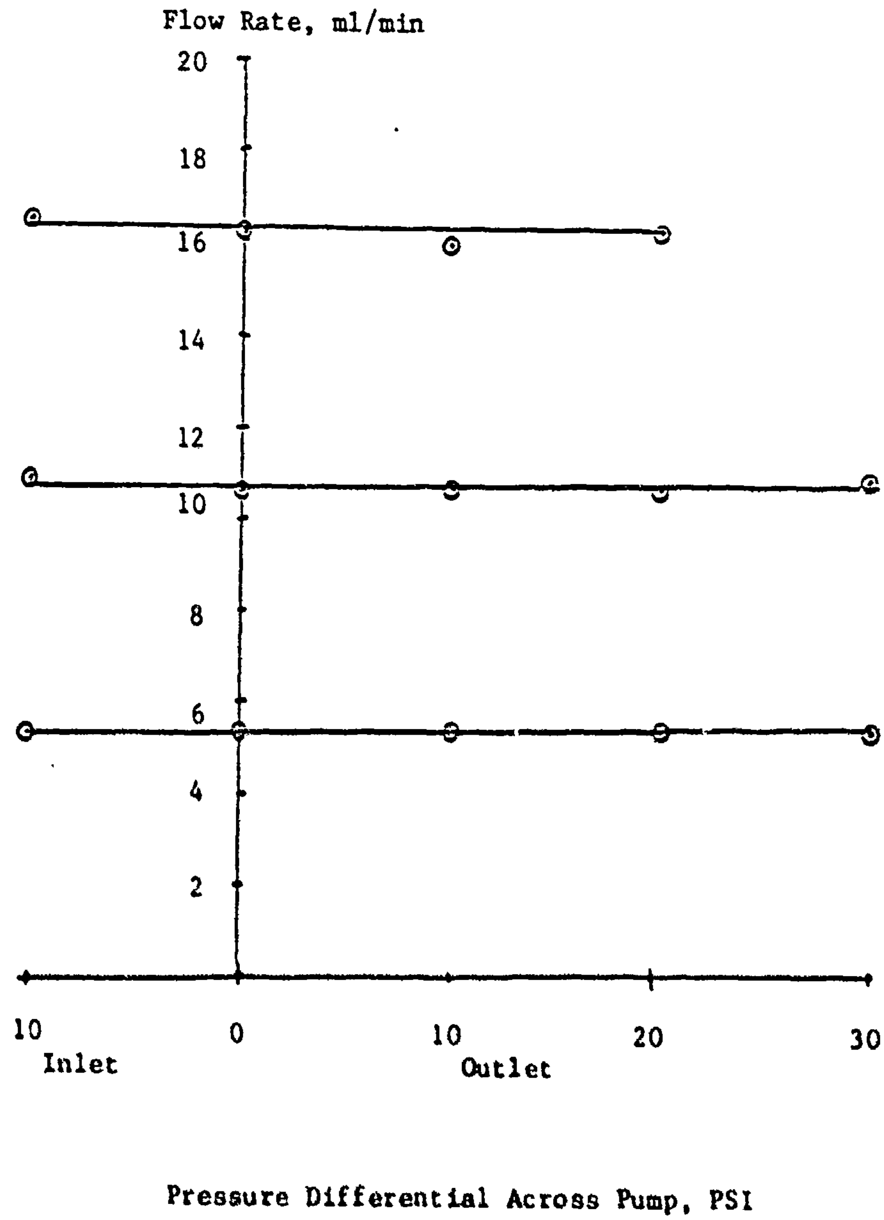


Figure 11

Flow Rate vs Pressure Differential
.172 cc/rev, MTHPA
.297 cc/rev, Epon 826
Static Mixer

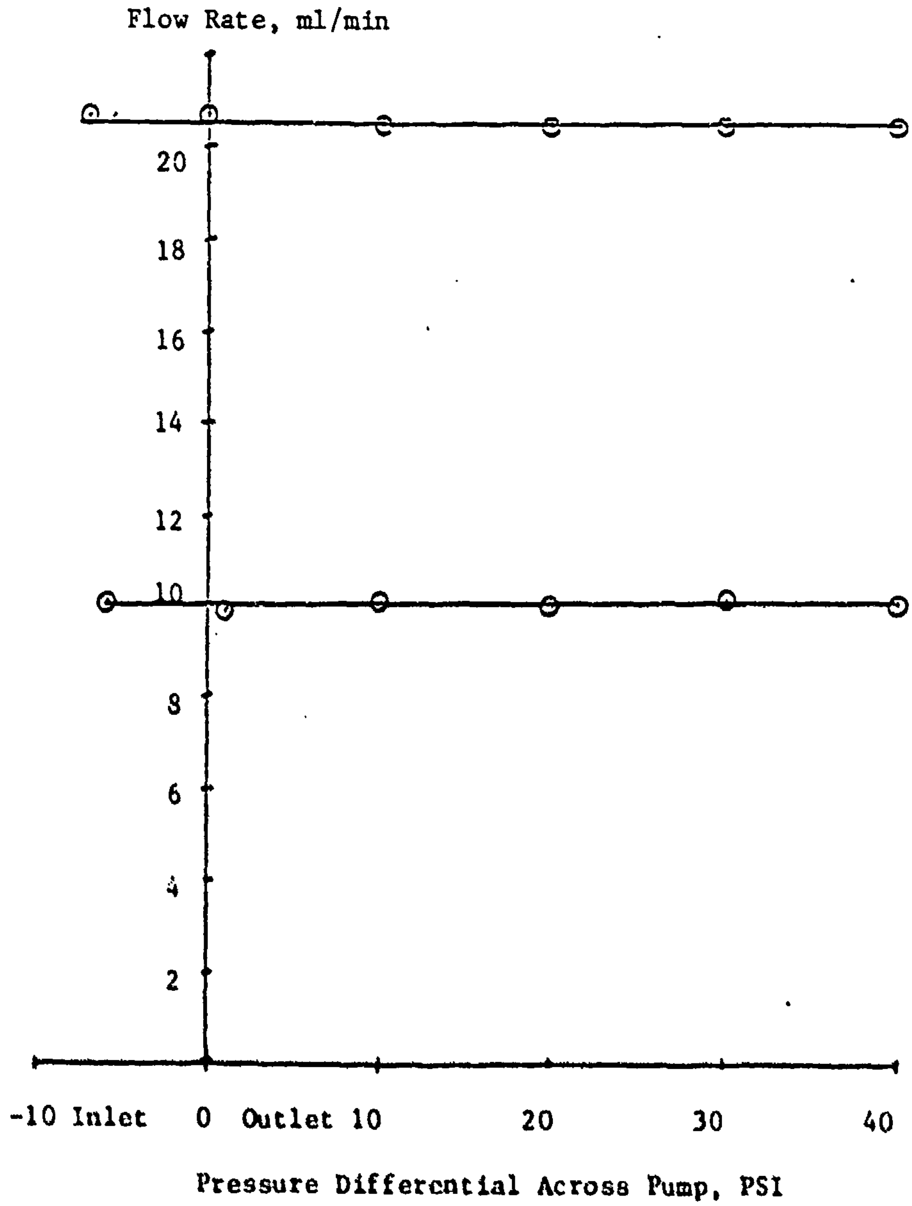
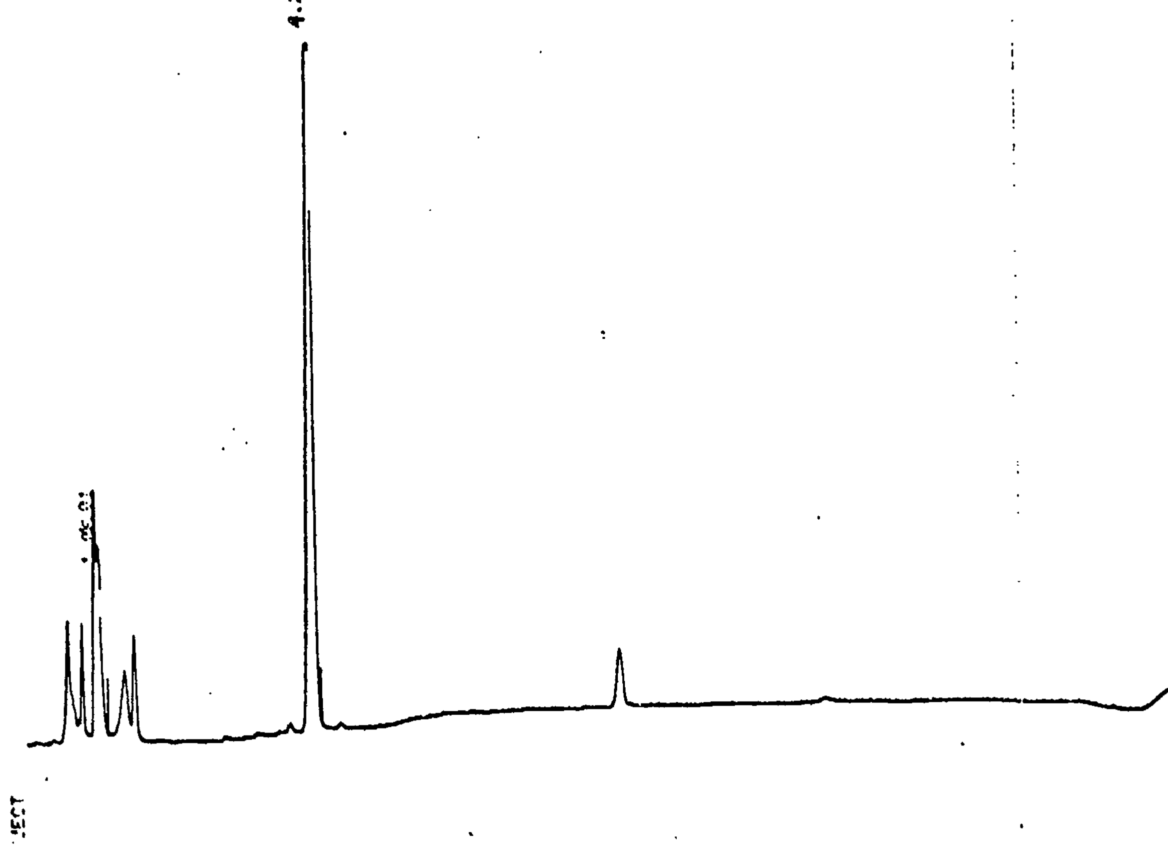
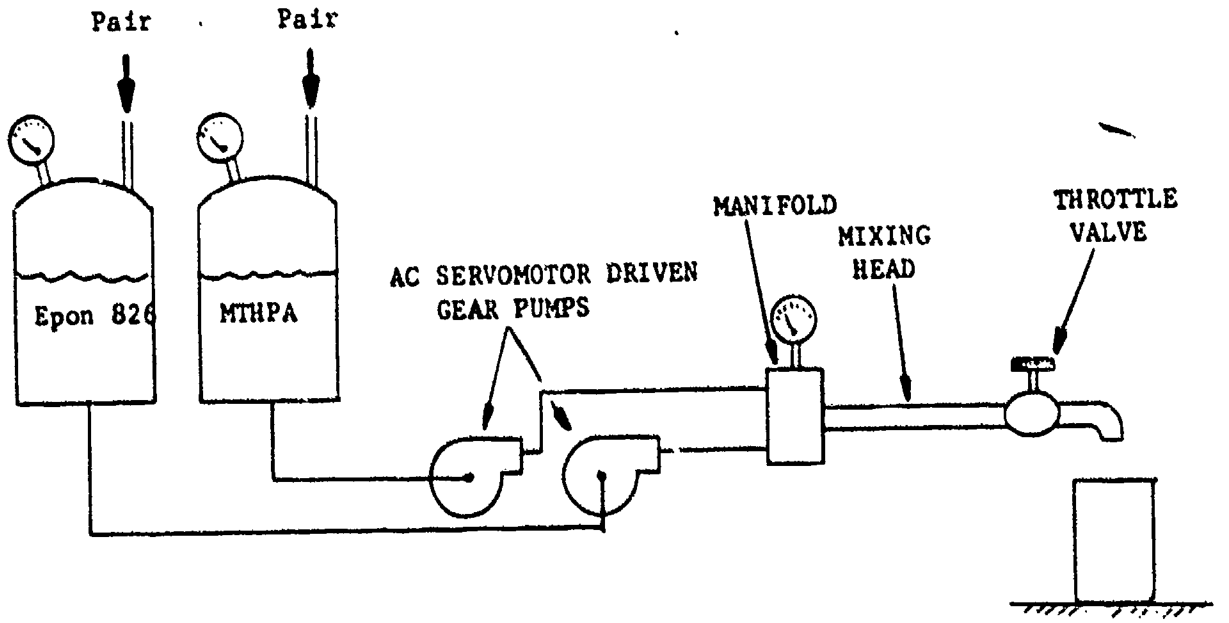


Figure 12

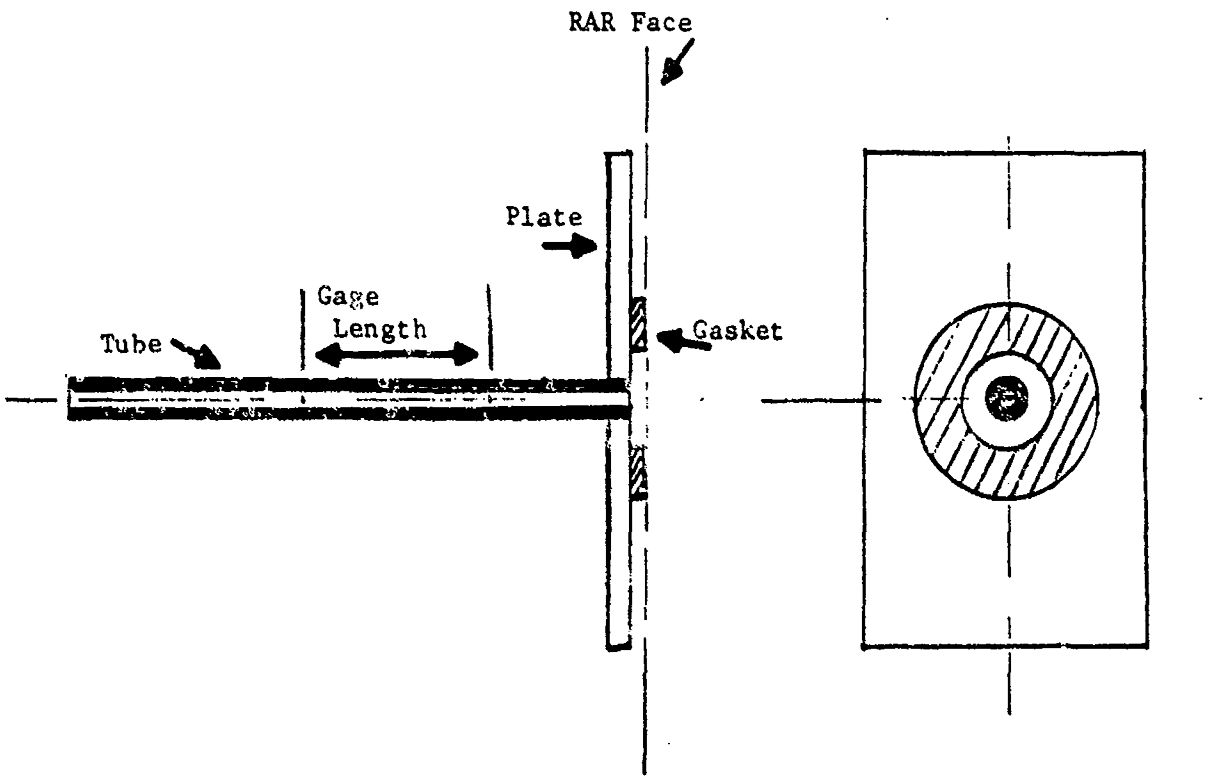


HPLC Output for Epon 826 Resin



Test Apparatus fo Sampling for HPLC Analysis

Figure 13



RAR Flow Sampling Tool

Figure 14

RAR Pressure vs Flow Rate
Constant Flow Resistance
Low, Medium, High Fluid Viscosities

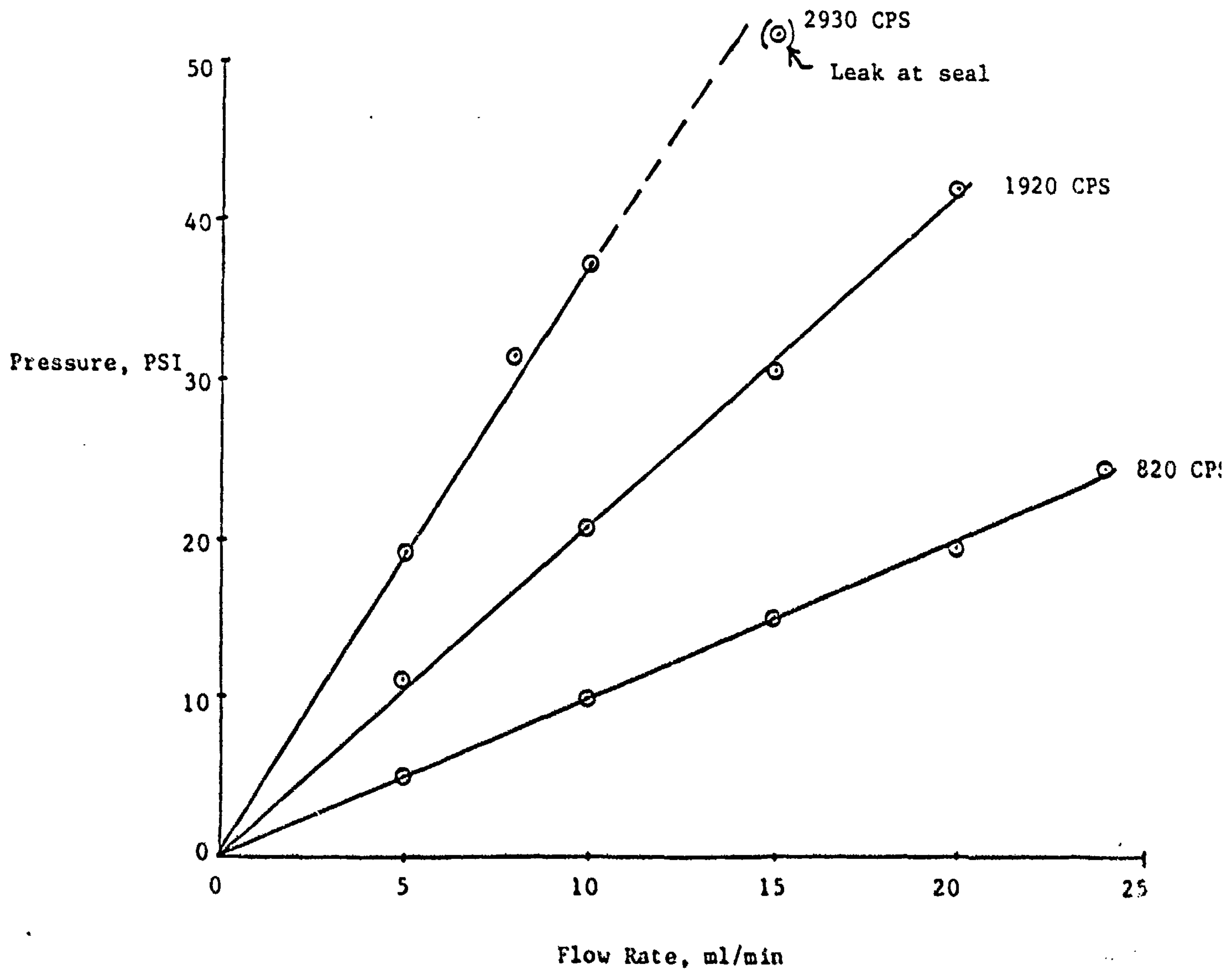


Figure 15

RAR Flow Pressure vs Viscosity
@ 10 ml/min

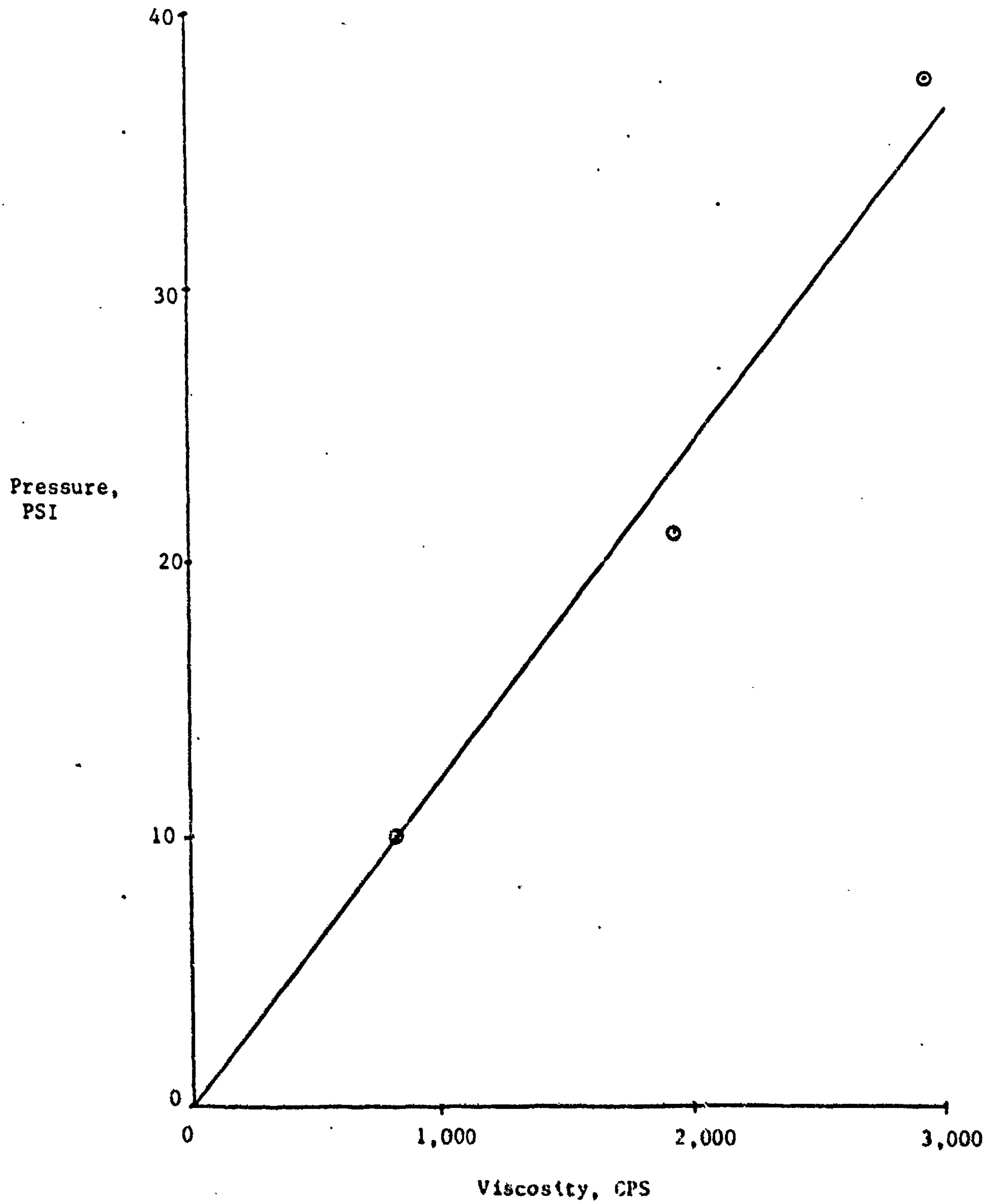


Figure 16

RAR Flow

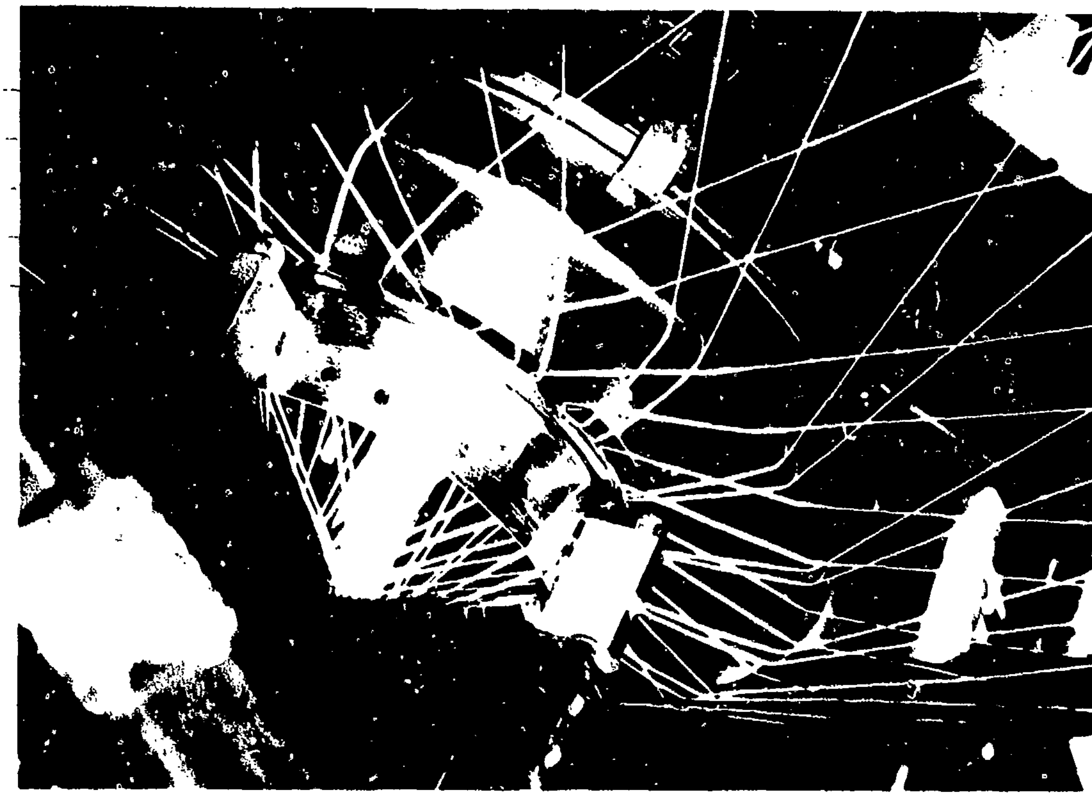
Figure 18

RAR Flow
Sampling

Figure 17

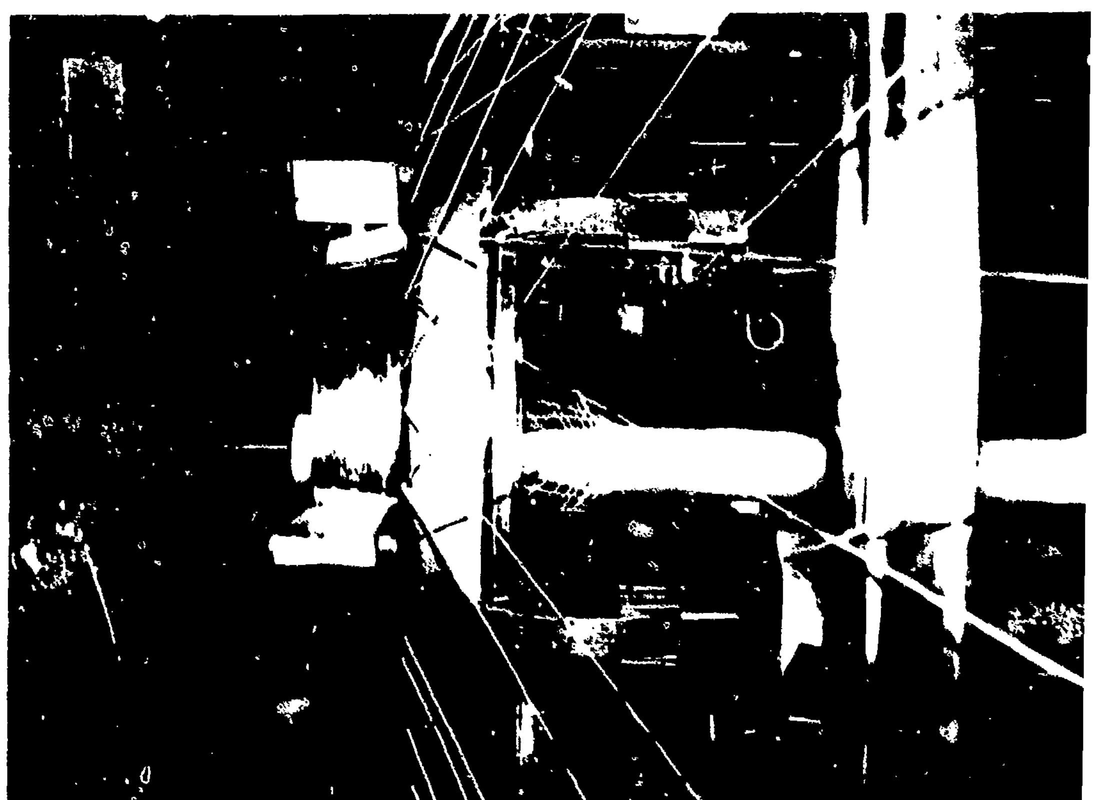
Fibers Wiping RAR Face

Figure 19



Forward Wet Braiding

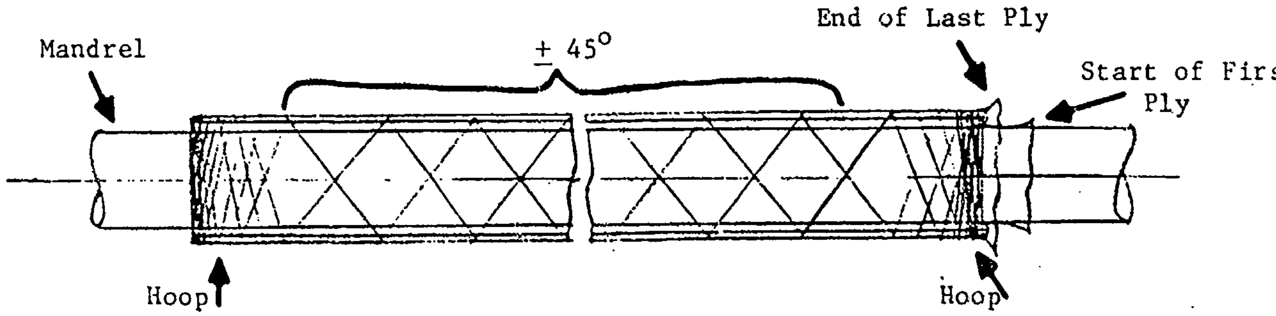
Figure 20



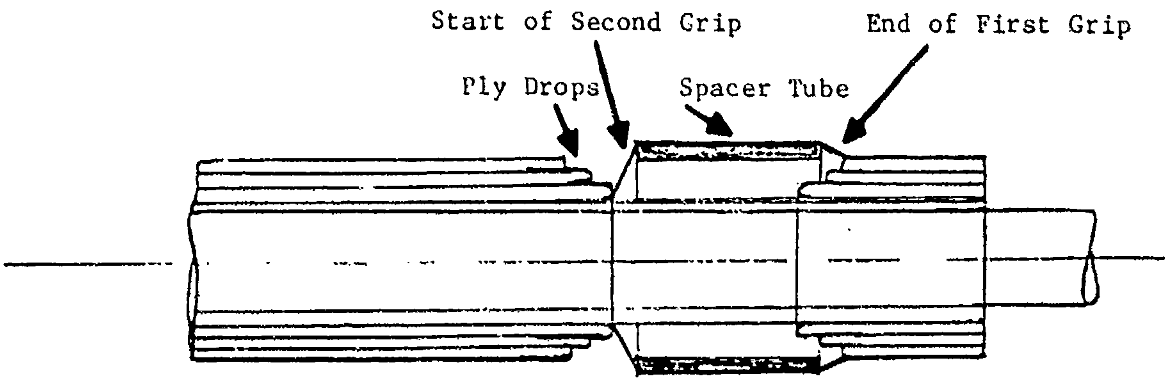
Reverse Wet Braiding

Figure 21

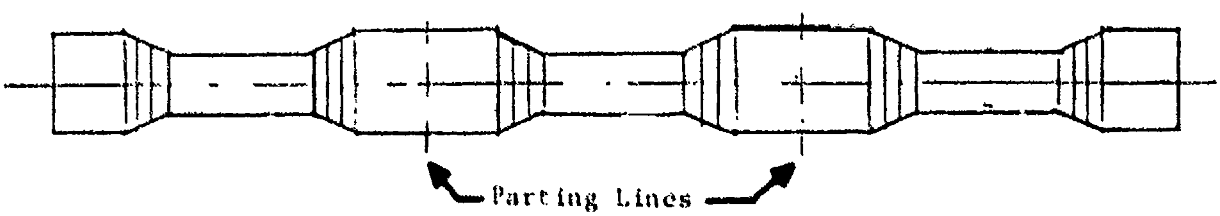
Gage Length



Grip Buildup



Trimmed and Removed from Mandrel



Test Specimens

Figure 22

Table 1
HPLC Results for Two Component Pumping System Using Epon 826/MTHPA

Sample No.	Predicted	Measured	Air Pressure PSI	Manifold Pressure PSI	Pressure Differential PSI	Weight % Epon 826		% Deviation in Wt. % Compared to:	
						Predicted	HPLC	Predicted	Reference Sample
Reference Sample	--	--	--	--	--	55.25	57.6	4.3%	--
P4-1	10	10.06	10	4	- 6	55.25	57.0	3.2%	1.0%
P4-2	10	10.30	10	40	+ 30	55.25	58.1	5.2%	0.9%
P4-3	20	20.64	10	7	-3	55.25	57.6	4.3%	0.0%
P4-4	20	20.40	10	40	+ 30	55.25	57.0	3.2%	1.0%

TABLE 2 Flow Distribution Data
(Per Tests 22, 23, and 24)

(CPS) μ	(ml/min) Q	(PSI) P	% 12:00/6:00
820	5	5	82
	10	10	76
	15	15	88
	20	20	96
	25	25	88
1,920	5	10.5	96
	10	21	95
	15	31	87
	20	41.5	107
2,930	5	19	79
	8	30	89
	10	37	98

TABLE 3
Fiber Parameters

Type	Size	Sizing	Twist (Turns/Inch)
Glass (OCF)	Yarn, 8 Ends,	493	3.8
	Roving, 750 Yield	449AA	0.25
		[Epoxy Compatible]	
Kevlar (DuPont)	4260 Denier	None	0
			0.25
Carbon (Celion)	12K	EPO 3	0
		[Epoxy Compatible]	0.6
			1.5

TABLE 4
Results for Wet Braided Parts Cured on Mandrel Without Compaction

Trial Run No.	Predicted Volume Fraction Vf	Actual Fiber Volume Fraction Vf	Actual Void Volume Fraction Vv
#3 Glass	64	62.9	2.11
#5 Glass		60.3	3.30
#6 Kevlar		61.2	3.10
#7 Kevlar	66	63.9	1.70
#8 Kevlar		60.3	3.30
#9 Carbon	62	39.8	3.70
Glass (Triaxial)	56	56.8	2.40

Note: The low fiber volume fraction obtained from Trial Run No. 9 is attributed to poor compaction of the braid. This Trial used an untwisted, 12 k carbon fiber tow. Substantial fiber damage occurred as this tow passed through the standard Mossberg carrier mechanism. The broken fibers of adjacent tows tangled, preventing the formation of a uniform, property compacted braid. This problem was later corrected by using twisted carbon fiber tow and by making modifications to the Mossberg carriers. These improvements were not made in time to perform additional volume fraction tests before the contract completion date.

Appendix A--Pump Control System

Operator Control

The control added to the Interphase Robot enclosure at the Watervliet Arsenal has two selection switches:

- o PUMPS OFF/ON

- o PUMPS JOG/AUTO

The PUMPS ON/OFF switch permits the pumps to be shut off for running dry parts or set up. When the in the OFF position, the switch inhibits the Servo Amplifier, thus the pump motors will not move regardless of program commands. When the switch is in the ON position, the Servo Amplifier and Servo Motors are enabled but will not move without a command from the G & L control (the control in the Interphase Robot).

The PUMPS JOG/AUTO switch, in AUTO, permits the pumps to run under Automatic Cycle as part of a programmed sequence in which the pump rate is entered as a part of the robot program sequence in ml/min of the catalyst and resin. In this mode, the pumps are just another element in the overall robot program. In the JOG mode, the pumps can be turned on at a rate set by the robot control. This is useful when filling the Resin Applicator Ring or in flushing the system after use. In JOG, the rates are entered on the Interphase control and the pumps turned on. The pumps will run until shut off.

Theory of Operation

The pump motors are Servo motors held in a velocity loop through a Westamp Servo drive and position loop through the G & L CNC control which is part of the Interphase robot.

The pump motors are 40 in/lb continuous-torque motors with a 7 volt/1,000 rpm Tach and resolver in a package. The motor power is provided by Westamp 721 Servo Amplifier. The Tach feedback from the motor is fed into the amplifier where it is compared with the velocity command from the G & L. The Servo Amplifier keeps the motor rpm, and thus the pump rate, constant and at the velocity set by the G & L control. There are two indicators in series with the pump motors to limit the current spikes from the amplifier.

The G & L control excites the resolver with a sine and cosine sign. It then picks up the rotor phase angle, from which it determines the angular position of the motor shaft at any time. The control keeps track of this position, and the rate the position changes, to maintain the set velocity

(pump rate in ml/min). The G & L Control is programmed to reset the position to zero every 1,000 increments (one shaft revolution), so the pumps are not held to an absolute position, only a constant velocity.

The G & L control will command the pump movement only when a value of flow rate has been set for that pump and all necessary interphase conditions are met. In JOG, the control will permit pump flow when the G & L control is turned on and a rate of flow is set. In AUTO, the pump will move along with the other axis of the robot system.

Trouble Shooting

A. One motor runs OK and the other will not.

1. Check voltage on terminals 1 and 2 (Motor 1) or 3 and 4 Westamp. A high voltage (over $\pm$ 20 volts) indicates the motor is being told to move. If the motor is hot, the thermostat in the motor may have opened. An open wire to the motor can be checked by measuring resistance (power off) between wires 87,88, or 85, 86. It should measure about 0.45 ohms. The motors are identical so they can be exchanged as a test for a faulty motor (all wires must be moved from one motor to the other). The motor should turn freely when the power is off. A 12v battery (car battery or lift truck battery) will make the motor turn at about 300 rpm (apply the battery to the motor leads with all other power off). While running at 300 rpm the Tach voltage should read about 2 to 2.5 VDC. A 25 percent error in Tach voltage or rpm will not significantly affect system operation.

2. If the voltage between terminals 1 & 2, or between 3 & 4 is zero even when the cnc is commanding a move, the problem could be in the drive. The two-axis boards are identical and may be exchanges as a test.

3. When the computer is commanding a move, the voltage on the G & L control axis terminals ch.5 or ch.6 should show a voltage of up to $\pm$ 10v when the move is not being executed.

4. The G & L control can be set up to read the position as the motor shaft is moved by hand as a way to verify the functioning of the feedback resolver.

B. Neither motor will run

1. Check for 72 volts AC going to the drive wires 89 & 90.

2. Verify the fan on the drives is running (110 v is present).

3. Make sure the SERVO ON switch is on.

4. Make sure a pump rate is commanded.

C. The motors run rough

1. Check the Tach brushes by measuring the Tach resistance as the motor shaft is turned slowly by hand with all power off.

2. Check the motor brushes.

3. Look in a motor brush hole with a light to see if the commutator is reasonably clean and free from deep burns.

D. At the G & L control, set up to read the position of a pump axis and verify that the position changes in a linear manner when the motor shaft is turned by hand (the SERVO ON/OFF switch should be OFF).

Major Parts

1 each WESTAMP INC. A7212, Two-Axis Servo Chassis

2 each WESTAMP INC. A721X-110, Axis Servo Board

1 each WESTAMP INC. TRANSFORMER 110 v P-72vs for A7212 chassis

2 each WESTAMP INC. MT 235 Servo Motor with Resolver feedback

2 each WESTAMP INC. Inductors for MT235 Servo Motor

Appendix B

TR #	1	2	3	4	5	6
Specimens	First Wet Braiding, Foam Cores	1" ID, ± 45° Tubes	1" ID, ± 45° Tubes with Grips	1" ID, ± 45° Tubes with Grips	1" ID, ± 45° Tubes with Grips	1" ID, ± 45° Tubes with Grips
Fibers	Kevlar 7100 Denier No Twist	S-2 Glass, 8 Ends CG150, 1/3 3.8 TPI	S-2 Glass, 8 Ends CG150, 1/3 3.8 TPI	S-2 Glass, 8 Ends CG150, 1/3 3.8 TPI	S-2 Glass, 8 Ends CG150, 1/3 3.8 TPI	Kevlar 49, 4260 Denier No Twist
Resin	Epoxy, Pre-mixed	Tactix 138 MTHPA BDMA Pre-Mixed	Tactix 138 MTHPA BDMA Pre-Mixed	Epon 826 MTHPA BDMA Pump Mix	Epon 826 MTHPA BDMA Pre-Mixed	Epon 826 MTHPA BDMA Pre-Mixed
64 C Braider	125 PPM	125 PPM	125 PPM	125 PPM	125 PPM	125 PPM
Mandrel Drive		Precision	Precision	Precision	Precision	Precision
Mandrel	Round and Trapezoidal Rohacell	Aluminum Steel	Aluminum	Aluminum	Aluminum	Aluminum
Pumps	1 Micropump	1 Micropump 9.3 ml/min	1 Micropump 7.5 to 9.0 ml/min	2 Micropumps 10.8 ml/min	1 Micropump 9 ml/min	1 Micropump 9 to 21 ml/min
RAR		#13 Pins, 950-25 Paper	#13 Pins, 950-25 Paper	#13 Pins, 950-25 Paper	#13 Pins, 950-25 Paper	#13 Pins, 950-25 Paper
Cure		4 hr @ 180°F 3 hr @ 350°F	4 hr @ 180°F 3 hr @ 350°F	4 hr @ 180°F	4 hr @ 180°F 3 hr @ 350°F	4 hr @ 180°F 3 hr @ 350°F
Comments, Testing		Sent for Mech. Testing	Sent for Mech. Testing, Burnoffs	Mix Ratio Fell Off.	Sent for Mech. Testing, Burnoffs	Fiber Knotting, Acid Digestion, Resin "Ran"

Appendix B (Cont.)

TR #	7	8	9	10	1.	12
Specimens	1" ID, ± 45° Tubes with Grips	1" ID, ± 45° Tubes with Grips	1" ID, ± 45° Tubes, No Grips	1" ID, ± 45° Tubes with Grips	1" ID, ± 45° Tubes With Grips	1" ID, ± 45° Tubes With Grips
Fibers	Kevlar 49 4260 Denier No Twist	Kevlar 49 4260 Denier 1/4 TPI	Celion, 12K No Twist	Kevlar 49 4260 Denier 1/4 TPI	S-Glass 750 Yield 1/4 TPI	S-Glass 750 Yield 1/4 TPI
Resin	Epon 826 MTHPA BDMA Pre-Mixed	Epon 826 MTHPA BDMA Pre-Mixed	Epon 826 MTHPA BDMA Pre-Mixed	Tactix 138 H 41	Epon 826 MTHPA BDMA Pump Mix	Epon 826 MTHPA BDMA Pump Mix
64 C Braider	125 PPM	125 PPM	125 & 94 PPM	125 PPM	125 PPM	125 PPM
Mandrel Drive	Precision	Precision	Precision	Precision	Precision	Precision
Mandrel	Wood and Aluminum	Aluminum	Wood and Aluminum	Aluminum	Aluminum	Aluminum
Pumps	1 Micropump 12 ml/min	1 Micropump 12 ml/min	1 Micropump 13.2 to 18 ml/min	2 Nichols-Zenith 12 ml/min	2 Nichols-Zenith 9 to 13.6 ml/min	2 Nichols-Zenith 11 to 15 ml/min
RAR	#13 Pins 950-25 Paper	#13 Pins 950-25 Paper	#13 Pins 950-25 Paper	#13 Pins 950-25 Paper	#14 Pins 950-25 Paper	#14 Pins 950-25 Paper
Cure	2 hr @ 180°F 1 hr @ 212°F 3 hr @ 350°F	4 hr @ 180°F 3 hr @ 350°F	4 hr @ 180°F 3 hr @ 350°F	1 hr @ 266°F 2 hr @ 320°F	4 hr @ 180°F 3 hr @ 350°F	4 hr @ 180°F Dwell @ 320°F 3 hr @ 350°F
Comments, Testing	Acid Digestion, Resin "Ran"	Mech. Test, Acid Digestion, Resin Blistered	Fiber Matting, Acid Digestion	Mech, Test, Fiber Knotting	Mech. Test	Mech. Test

Appendix B (Cont.)

TR #	13	14	15	16	17	18
Specimens	1" ID, ± 45° Sleeve with Grips	1" ID, ± 45° Tubes with Grips	1" ID, ± 45° Tubes with Grips	1" ID, Triaxial Tubes, No Grips	1" ID, ± 45° Tubes, No Grips	1" ID, ± 45° Tubes, No Grips
Fibers	Celion, 12K 0.6 TPI	Celion, 12K 0.6 TPI	Kevlar 49 4269 Denier 0.3 TPI	S-Glass 750 Bias, 0.6 TPI, 1250 Warp, No Twist	Celion 12K 1.5 TPI	S-Glass 750 Yield 0.6 TPI
Resin	None	Epon 826 MTHPA BDMA Pump Mix	Tactix 138 H 41 Pump Mix	Tactix 138 H 41 Pump Mix	Tactix 138 H 41 Pump Mix	Tactix 138 H 41, BYK-A-520 Air Release Pump Mix
64 C Braider	125 PPM	125 PPM	125 PPM	125 PPM	125 PPM	125 PPM
Mandrel Drive	Precision	Precision	Precision	Precision	Precision	Precision
Mandrel	Aluminum	Aluminum	Aluminum	Aluminum	Aluminum	Aluminum
Pumps	None	2 Nichols-Zenith 20 ml/min	2 Nichols-Zenith 20 ml/min	2 Nichols-Zenith 20 ml/min	2 Nichols-Zenith 20 to 25 ml/min	2 Nichols-Zenith
RAR	No Internals	#14 Pins, 950-25 Paper,	#14 Pins, 909-25 Paper, Heated	#14 Pins, 909-25 Paper, Heated	#14 Pins, 909-25 Paper, Heated	#14 Pins, 909-25 Paper, Heated
Cure	None	4 hr @ 180°F 3 hr @ 350°F	1 hr @ 266°F 2 hr @ 320°F	1 hr @ 266°F 2 hr @ 320°F	1 hr @ 266°F 2 hr @ 320°F	1 hr @ 266°F 2 hr @ 320°F
Comments, Testing	Better Compaction than with untwisted Material	Mech. Test	Mech. Test	Mech. Test	Mech. Test	Mech. Test

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COMPUTER CONTROLLED RESIN IMPREGNATION FOR COMPOSITE BRAIDING
A. H. Kruesi and G. H. Hasko
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Rensselaer Technology Park
105 Jordan Road
Troy, NY 12180
Technical Report MTL TR 87-23, April 1987
67 pp. illus.-tables, Contract DAAG46-85-C-0059
D/A Project 1L665502MM40
Final Report, September 1985 to December 1986

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Textile processes such as braiding may significantly reduce the cost of advanced composites. Braiding can be readily automated and offers high fiber deposition rates and geometric versatility. Previously, the use of braiding was limited because of the difficulty in wetting fibers moving in a complex path. A novel resin impregnation system has been developed to adapt braiding to automated production of advance composites. A tubular braider has been equipped with a computer numerical control system. Two axes are used to drive pumps which feed resin and catalyst to the resin impregnation ring. The mix ratio and resin volume fraction can be coordinated in software with braider and mandrel speeds to fabricate parts which have complex features. Test specimens have been fabricated with glass, Kevlar, and carbon fibers. Fiber wetting and void content were evaluated from microphotographs of parts cured on a mandrel without compaction. Burn-off test indicated that fiber volume fractions are in excess of 60 percent. Applications for the process include rotor blades, stiffeners, drill risers, and similar structural components. This work was supported by the U.S. Army Materials Technology Lab under the Small Business Innovation Research (SBIR) program.

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